U.S. CONGRESS

JOINT COMMITTEE ON ATOMIC ENERGY

Hearings 1959
Volume 2

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1959b

CONTENTS

Industrial radioactive waste disposal
volume 2 Jan 28- Feb. 3, 1959

INDUSTRIAL RADIOACTIVE WASTE DISPOSAL

HEARINGS

BEFORE THE

SPECIAL SUBCOMMITTEE ON RADIATION

OF THE

JOINT COMMITTEE ON ATOMIC ENERGY

CONGRESS OF THE UNITED STATES

EIGHTY-SIXTH CONGRESS

FIRST SESSION

ON

INDUSTRIAL RADIOACTIVE WASTE DISPOSAL

JANUARY 28, 29, AND 30; FEBRUARY 2 AND 3, 1959

VOLUME 2

Printed for the use of the Joint Committee on Atomic Energy

UNITED STATES
GOVERNMENT PRINTING OFFICE
0-37457 WASHINGTON : 1959

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NOTE

This is Volume 2 of four volumes of the record of "Hearings on Industrial Radioactive Waste Disposal." It covers the first half of the current waste disposal research and development program. It describes and discusses the treatment and controlled dispersal of low and intermediate level wastes to the atmosphere, surface waterways, the ground, and the ocean and environmental investigations associated with this phase of the development program. Volume 1 covers the portion of the hearings concerned with the origin and nature of various types of radioactive wastes evolved from nuclear energy activities and operations in use to manage these wastes at various AEC and other installations. Volume 3 covers the second half of the current waste disposal research and development program. It describes and discusses the handling, treatment, and proposed ultimate disposal systems for highly radioactive wastes that are primarily evolved from irradiated fuel reprocessing plants and discusses the future estimates and economics of disposal of radioactive wastes. It also includes a summary of environmental factors related to these estimates and a discussion of the industrial viewpoint of the radioactive waste problem. Volume 4 discusses the activities of Federal and State governmental agencies in radioactive effluent control and administrative relationships between these agencies. The international aspects of the problem are also dealt with in this volume.

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INDUSTRIAL RADIOACTIVE WASTE DISPOSAL

THURSDAY, JANUARY 29, 1959—Continued

CONGRESS OF THE UNITED STATES,
SPECIAL SUBCOMMITTEE ON RADIATION,
JOINT COMMITTEE ON ATOMIC ENERGY,
Washington, D.C.

AFTERNOON SESSION

WASTE DISPOSAL RESEARCH AND DEVELOPMENT PROGRAM

Representative HOLIFIELD. The committee will be in order.

Continuing our waste disposal hearings, we will ask Dr. J. A. Lieberman of the AEC, charged with the waste disposal research and development program, to come forward.

Dr. Lieberman. It is nice to have you with us, Doctor. You may proceed.

STATEMENT OF DR. J. A. LIEBERMAN,[5] CHIEF, ENVIRONMENTAL AND SANITARY ENGINEERING BRANCH, DIVISION OF REACTOR DEVELOPMENT, U.S. ATOMIC ENERGY COMMISSION

Dr. LIEBERMAN. Thank you, sir.

Mr. Chairman and members of the committee, before going on with my testimony, I did want to note that as a result of my associate, Walter Belter, and myself having had the privilege of working with Mr. Toll of your staff in helping to develop the agenda for these hearings, we have had the opportunity to scan the material that has been submitted. I feel sure that the record of these hearings will be the most comprehensive collection of information ever assembled on this subject and the final record will be an invaluable reference document.

The U.S. Atomic Energy Commission is engaged in an extensive research and development program in the handling, treatment, and disposal of a wide variety of radioactive wastes resulting from a number of different nuclear energy activities. The origin and nature of these wastes have been discussed previously. For the most part, the technical direction and administration of this program is assigned to the Reactor Development Division. However, some de-

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velopment activities specifically related to production and other operations are carried out at several field installations and are not under the direct administration of the Reactor Division, even though the technical coordination is through the Environmental and Sanitary Engineering Branch in that Division.

Some measure of the extensiveness of the program is given by the distribution of the organizations and projects that comprise the program. Individual investigative projects that are integrated components of the overall program are being carried out at all the AEC national laboratories and the major AEC production sites; through contracts at a number of State and private universities from Massachusetts to North Carolina and California, and from Illinois to Texas; through working agreements and transfer of AEC funds to some half dozen technical Federal agencies; and by contract with private research organizations.

The general but basic objectives of the AEC waste disposal research and development program can be listed as follows:

First, to develop practical systems for the final disposal or long-term management of highly radioactive wastes associated primarily with the chemical reprocessing of irradiated nuclear fuels;

Second, to evaluate quantitatively the dilution and/or concentration factors in nature in order to determine the degree of treatment actually required prior to release of effluents to the atmosphere, ground, or waterways;

Third, to obtain increased knowledge of the fundamental phenomena and processes involved in the handling and disposal of radioactive wastes so that more efficient and economic systems may be devised.

In addition, other less technical, but perhaps equally important purposes, are served by the research and development activities.

For example, the program supplies a valuable mechanism for integrating the nationwide efforts of private and governmental agencies in dealing with waste disposal and environmental problems of American industry with the newer and, as you have heard, in some cases, unique operations of the nuclear energy industry. This allows advantage to be taken of the specialized experience and competency of various experts in these agencies. The program in a number of cases has also been the framework for assisting and working with State and local officials concerned with waste disposal and environmental problems in areas of their jurisdiction. This has enabled a better understanding of related problems of the nuclear energy industry in these fields of public responsibility and concern.

It was quite obvious early in the program that the attack on radioactive waste and associated environmental problems required the detailed and continuing attention of numerous disciplines, including geologists, hydrologists, meteorologists, chemists, chemical engineers, sanitary engineers, biologists, and others. Thus the excellent and close continuing working relationships with other agencies such as the U.S. Geological Survey, U.S. Weather Bureau, U.S. Public Health Service, U.S. Coast and Geodetic Survey, the U.S. Bureau of Mines, the National Academy of Science, and others were established.

Both oral testimony and statements for the record will be submitted by scientific representatives of several of these agencies.

In general, the technical projects being carried out in the research and development program can be categorized according to the nature of the wastes under consideration and the way in which they are being handled, or the way it is proposed that they be handled some time in the future. The kind of environment in which they are considered is, of course, also intimately involved.

The two generalized approaches to, or techniques of, waste management have been noted previously and need not be discussed in detail at this time. They are characterized by the phrases, "concentrate and contain" and "dilute and disperse" which you have previously heard. The "dilute and disperse" approach is applicable to wastes that normally contain small concentrations of radioactive materials, or in which the concentration can be reduced to small quantities by treatment, and to environments with adequate dilution capacity.

The term "dispersal" is used here to describe the discharge of wastes to the environment in a manner that permits little or no direct control by man over the fate of the wastes following their discharge. The discharge of liquid wastes to surface waterways or gaseous wastes to the atmosphere are examples of dispersal, and these have been described.

The "concentrate and contain" technique must be utilized for wastes—the so-called high level wastes—that contain more radioactive materials than can be assimilated safely by the environment. Systems for final disposal of these wastes must be such that they—

(*a*) Permit continuing, long-term control by man over the wastes, and/or

(*b*) Assure the wastes will be contained essentially at the point of disposal so that man, his environment and his resources are not adversely affected. As you have heard, the time element involved is literally hundreds of years.

The early phase of the research and development program was primarily concerned with the handling and disposal of large-volume, low-level liquid effluents, gaseous and particulate wastes, and assessment of the effect of relatively low levels of radioactive materials discharged to the environment on public sewage treatment and water supply facilities. Work was also done on waste processing and treatment systems for various types of wastes. This activity was carried out in a coordinated program at the national laboratories and by contract at various universities and industrial laboratories and by other Government agencies.

Examples of early accomplishments in the program include:

1. Determination of limitations and feasibility of using biologic sewage treatment processes for low level wastes.

2. Determination of the efficiency of standard water treatment methods in removing radioactivity.

3. Development and commercial production of high efficiency air filters and publication of a handbook on aerosols and a handbook on air cleaning, and

4. Development of specific waste treatment systems including evaporators, precipitation plants and incinerators.

Also early in the program, extensive meteorologic, geologic and hydrologic programs were initiated under letters of agreement with the U.S. Weather Bureau and the U.S. Geological Survey to define and assess important environmental factors involved in the location, design, construction and operation of nuclear installations. Examples of accomplishments from this work include:

1. Detailed meteorologic, geologic and hydrologic reports on a number of AEC operating areas.

2. A quantitative evaluation of dilution factors in the Mohawk River in New York which enable the elimination of treatment of low-level wastes at Knolls Atomic Power Laboratory and their safe discharge directly to the river, and,

3. Publication of a compendium of important meteorologic information as a report entitled "Meteorology and Atomic Energy." I understand that this document has been translated to and published in several foreign languages. In addition, numerous detailed technical reports of work in this field were published.

Witnesses immediately following me will give more detailed descriptions of development activity related to this dilution and disperse approach.

In the last few years there has been increased emphasis on development activities related to problems of high level wastes—the highly radioactive liquid effluents originating in the chemical reprocessing of irradiated fuels. As differentiated from processing, treatment or storage of these wastes, little work outside the laboratory has yet been done on full-scale final disposal systems.

With regard to treatment and processing, there has been a substantial investigative effort on the fixation of radioactive material in chemically inert solid media. The objective is to so convert the wastes into a solid, nonleachable material that they may be permanently stored, that is, disposed, in specific environments with negligible long-term hazard. Two general schemes for accomplishing this objective have been under development at several AEC and university laboratories.

One involves the conversion of the highly radioactive liquid wastes to a solid oxide form by heating in some kind of liquid-solid contactor. Work done at the Idaho chemical processing plant, Argonne National Laboratory, and the Brookhaven National Laboratory are the prime examples of major steps in this approach. This work will be described in some detail in later testimony.

The other general scheme involves incorporating the radioactive material either physically or chemically in clays, glasses, or synthesized crystal minerals such as feldspars or micas. These two general ideas can fit together in that the solid oxide may be used as a starting material in a further fixation system, or the oxide material may be put through a leaching step to remove the soluble radioactivity and subsequently fixing the leach solution in another solid material.

Enough laboratory work has been done to indicate the technical feasibility of several such systems. Engineering development is farthest advanced at the Idaho chemical processing plant where a fluidized bed technique is being utilized to convert the liquid wastes to a solid oxide. At Idaho the detailed engineering design of a 60-gallon per hour prototype development unit has been completed under a contract with the Fluor Corp.

At the Brookhaven National Laboratory, preliminary engineering study of a rotary kiln plant and a clay fixation unit has been done. Generally in all of these system practical solutions to a number of important associated problems have yet to be demonstrated on an engineering scale. These problems include control of radioactive aerosols and gases, volatilization of specific fission products, and corrosion.

The possibility of direct disposal of high level wastes—I speak here now about the wastes associated with the chemical processing plants—into selected geologic formations has been under active consideration for about the past 2½ years. The feasibility, practicality and safety of such systems will be demonstrated only after extensive laboratory and field experiments which are just now being initiated. Engineering and economic analyses are in their early stages, but sufficient work has been done to justify pursuit of such approaches at least on a limited scale. Of the geologic formations proposed for this purpose in the United States, which include salt structures, deep synclinal basins, impermeable shales and certain deep porous formations, disposal into prepared cavities in salt appear to be most advanced in programing. Further discussion in this area is scheduled.

At the present time it would appear that an optimum solution, or I should say one optimum solution, to the problem of final disposal of highly radioactive liquid wastes would include the conversion of the waste into a solid, preferably, inert form and the long-term, essentially permanent, storage of these solids in a specially selected geologic formation such as a salt bed. As the degree of inertness of the solid material is increased, the requirements for the geologic formation become less restrictive. Interim tank storage would be an integral part of such a system.

Ocean disposal of high level wastes also has been given some consideration. Quite often confusion has resulted from an inadequate categorization of the quantity or nature of radioactive wastes involved in these discussions. For high-level fission product wastes emanating from chemical reprocessing, it appears conclusive that ocean disposal will not be feasible for many years to come, if at all. Required specific knowledge of oceanic behavior is so inadequate, and attendant engineering problems appear so complex, compared to other possible more advantageous solutions, that industry and government likely will be forced to systems inherently easier to directly control.

I would emphasize that this conclusion applies to the highly radioactive wastes resulting from chemical reprocessing of irradiated fuels and not to smaller quantities of low and intermediate level wastes in

solid, packaged, and liquid state. Extensive oceanographic research in support of low-level disposal operations at sea is in its early stages and will have to be increased as such operations expand.

Economic utilization of fission products may have an important bearing on the high level waste problem, but at this time the word "bearing" cannot be equated to "solution." Expanded use of and economic return from the waste streams is obviously an important goal, but it must be remembered that from the standpoint of protection of public health and safety, the necessity of safe disposal systems will remain.

In this connection, it is also important to emphasize again the technical distinction between recovery of specific fission products for useful purposes and the essentially complete removal of these fission products as a waste-disposal technique. The point to be emphasized is that utilization of fission products and waste disposal are not mutually exclusive considerations.

Intimately related to progress in waste management are substantial improvements in chemical reprocessing that have led to reduced waste volumes, reduction of nonradioactive dissolved solids in the wastes and other improvements in chemical reprocessing of irradiated fuels. This attack on the problem at its source represents an important contribution in the waste field.

There are other significant features of the radioactive waste development program listed below which must be noted in any discussion of the program:

1. As the nuclear-energy industry develops and goes into new areas, the need to develop more quantitative information on specific environments in relation to waste disposal will increase.

2. In high-level waste development work the program is in a transition stage. Laboratory work has proceeded to the point where further demonstration of practicality requires pilot-plant and field-scale experiments. If engineering feasibility and safety are to be demonstrated, such larger scale activities are essential and, accordingly, increased financial outlay will be required in the future.

3. The evaluation and selection of a site for a nuclear installation are intimately related to waste-management considerations. Results of the development program have contributed significantly to a better understanding of these relationships and evaluation of site problems.

4. One of the important dividends of the development projects carried out at the universities has been the training of scientists and engineers with special competencies in this unique and challenging field.

Changing technology is a characteristic of the nuclear-energy field. This is obvious. New reactors, new fuel elements, new chemical processes, and new uses of radiation may have a profound effect on the nature of the waste problem and its solution in the future. Therefore, it will be even more important to maintain a close working relationship between the various disciplines previously noted to assure that optimum solutions are developed for the problems that arise.

Although I think, as Dr. Wolman has already said, one has to be very careful to distinguish between aspiration, reality, and specu-

lation in this field, it is my own strong feeling that the development program has thus far found solutions to some of the waste problems—you have already heard testimony in this regard—and at least indicated solutions to others.

Much research, development, pilot-plant testing and field experiment and evaluation have yet to be done before firm engineering conclusions will be possible for all situations, but with proper attention to this phase of the industry, including the research and development program, I sincerely believe the industry can develop in a rational way without being hamstrung by its own wastes.

This is all I have to say, Mr. Chairman. The witnesses that will follow me will go into more detail on the technical aspects of the program.

Representative HOLIFIELD. Thank you, Dr. Lieberman.

Are there any questions by the committee?

Representative PRICE. I would just like to ask one or two, Mr. Chairman.

On page 9 on your second point you say:

> If engineering feasibility and safety are to be demonstrated, such larger scale activities are essential and increased budget support will be required in the future.

What is the time limit involved?

Dr. LIEBERMAN. Well, sir, I think I can aswer that question in this way: We are right now initiating, as an example, field-scale experiments in the disposal of these high-level wastes into salt cavities. This is being done initially with simulated waste; no radioactivity involved. This will be gone into in some detail later.

However, in these experiments—which obviously we hope will be successful and as a result of laboratory work we think our chances of success are pretty good—when we would go to using larger and larger quantities of radioactivity, the field equipment and facilities that will be required, as contrasted to what you can do in the laboratory, have to be on a larger scale, have to be done at locations away from the laboratory, and in general are much more expensive to do.

Representative PRICE. Have you ever set up any requirement for this larger scale program? Have you made any definite recommendations on it?

Dr. LIEBERMAN. Yes, sir; I think we have started, at least in a general way, that in order to accomplish these field-scale experiments, additional financial outlay and additional budget support would be required, and although I don't have the detailed numbers with me, I think that the increase in our own budget in the Reactor Development Division for this work is reflected in the proposed budget for fiscal year 1960, that is, the increase from 59 to 60 I think is accounted for mostly by the requirement for going into these field-scale experiments.

At the same time, I should also say, that in any development program, one always can use more money, and I think that with sufficient financial outlay that some of these approaches could be carried on in a parallel fashion.

For example, you have heard mention of deep wells. Well, at this stage of the game—in the next fiscal year—we don't propose to go into field experiments in the deep-well business.

Representative HOLIFIELD. Why don't you?

Dr. LIEBERMAN. I think the answer to that can be given two ways.

First, I feel that insufficient laboratory work has been done on the deep-well approach to enable us to interpret the results we would obtain from field experiments.

And secondly, I think, is the question of enough money to do everything.

Representative HOLIFIELD. We certainly have in the United States many locations, including arid locations, locations where the water table is favorable, abandoned oil wells that go down 10,000, 12,000, 13,000 feet deep, and it is customary for these gas-storage people to buy different strata where the oil has been removed and to store gas.

There is a big development going on out in Maryland now, as you know. That, of course, is the upper level. I am speaking of the lower levels. I know in my hometown in California an 8,000-foot strata of the oilfield was purchased by the gas people to store gas that comes from Texas to be used in the cold months of the year out there, so there are these great underground caverns which are, as far as I know, far below the fresh-water levels of underground stream fall that could be experimented on, it seems to me, without too much hazard.

Representative PRICE. Mr. Chairman, in that connection—I want you to answer his question, but also bring this in—at times have you not raised the survey due to availability of abandoned mines, and so forth?

Dr. LIEBERMAN. Yes, sir; I think I can answer, or at least comment on Mr. Holifield's remarks and yours also.

We have had a very close working relationship, as I have indicated, with the Geological Survey and the Bureau of Mines, and you will also hear from Mr. Moore, who is from the Standard Oil Co. In connection with particularly the abandoned oil-well approach, Mr. Holifield, we went to the American Petroleum Institute. This will be gone into in more detail in Mr. Moore's testimony.

They got together what I consider to be the top experts in the field in this country to consider this subject. They have come up with a report. I must say that we found out very early in the game that it was extremely difficult to define what one meant by an abandoned oil well with the new secondary recovery processes that are being developed. Wells that were once abandoned are now being reworked. There are also other technical considerations that relate to the number of holes that have been drilled in the formation and the consequent difficulty in knowing where the radioactive material might go.

Mr. Moore, I am sure, will go into this in more detail, but I will say this: when we first used the term or mentioned the term "abandoned oil well," we were given a very good course of instruction of what this really meant in the oil well business. I feel that we have been extremely fortunate in having the considered opinions and judgments of people with long-time experience in the petroleum business on this deep well approach. And I think you will be interested in hearing what Mr. Moore has to say on this subject.

Representative PRICE. What about abandoned mines, coal mines, and other types of products?

Dr. LIEBERMAN. Using the coal mines as an example, we have had discussions with the Survey and the Bureau of Mines on this, but I don't want to go into great detail here. The general association of abandoned coal mines with underground water has been, I would say, the limiting factor here. I am sure you are probably familiar with the problems that are involved in acid mine drainage from the coal mines in the eastern part of the country. When you ask the geologists to name a dry abandoned mine, they really apparently have to do some real thinking, so the association of these abandoned mines with potential water resources, in a large measure, has precluded the use of these facilities for the long-term disposal of these high-level wastes that we are talking about.

Representative PRICE. Let me ask you a question about your statement.

On page 4 in the last paragraph about the quantitative evaluation of dilution factors in the Mohawk River which enable the elimination of treatment of low-level wastes at Knolls Atomic Power Laboratory and their safe discharge directly to the river; would you elaborate on that somewhat?

Dr. LIEBERMAN. Yes, sir; I would be glad to.

A number of years ago, all the low-level wastes—we are talking now about the kinds of wastes that come from laboratories, using relatively small quantities of radioactivity and not the high level waste from chemical reprocessing—originally were all evaporating and the evaporator condensate, that is, the decontaminated steam that came off, was condensed and sent to the river, and the evaporator concentrate was drummed and shipped to Oak Ridge for burial. This was expensive.

The Mohawk River runs right by KAPL. The quantities of radioactivity involved were quite low, so the possibility of going out and attempting to measure how much dilution there was in the river that we could safely use suggested itself. We asked the Geological Survey, the General Electric Co., who operated the Knolls Atomic Power Laboratory, and the State Health Department of New York, to work with us in carrying out specific tests on the Mohawk River. We actually put radioactive tracers in the river and followed them to see what happened, how much of it went down the river, how much of it went to the bottom, how much of it the fish took, and so forth.

This was a meticulous study. It had to be because the water supply intake of the city of Cohoes was about 13 miles downstream from the outfall of Knolls. As a result of these tests, it was concluded that there was ample dilution capacity in the river so that at the point of use of this water, and this took into account the recreational use, the fish, and all the uses of the water resource, we could safely discharge these quantities of radioactivity and still meet the recommendations and requirements that were set up; that is, one-tenth the maximum permissible concentrations that have previously been described.

In other words, this was a deliberate investigative effort to determine in terms of numbers just what the dilution factor was there. I wouldn't want to be held to these numbers, but, as I recall, a dilution factor of somewhere in the order of 10 or 20 was required for the most hazardous isotope, and as a result of these investigations it was de-

termined that dilution factors of the order of thousands were available.

The one other point that should be made in connection with this, sir, is that with these operations there goes the requirement for continuous observation or continuous monitoring to make sure that at no time do we exceed the capacity of that particular environment to safely receive these radioactive materials. Therefore the Knolls Atomic Power Laboratory continuously takes water samples, fish samples, bottom samples, and so forth, to analyze them to make sure that the safe capacity of the river to receive radioactivity is not being exceeded.

Representative PRICE. A little further up on this same page, you were talking about the early accomplishment of the program, and you said the first two items include the determination of so-and-so. Could you tell us what those determinations were?

Dr. LIEBERMAN. Are you referring to the first paragraph there, sir?

Representative PRICE. Yes. Your first paragraph on page 4.

Dr. LIEBERMAN. Well, without going into great detail, I would say that the biologic sewage treatment processes that are common to the treatment of domestic sewage have only limited use for low-level radioactive waste. It depends on the specific isotope involved.

For example, if we were trying to decontaminate a waste from phosphorus, which the organisms used in their metabolism, if they weren't getting the phosphorus from someplace else, say from domestic sewage, the regular sewage treatment process would do a fairly decent job of removing the phosphorus from the waste. Ordinarily, if there were plenty of phosphorus around and the organisms in the process weren't particularly limited to the radioactive phosphorus, the processes would not do a very good job of removing phosphorus. The percent removals of radioactive material accordingly might vary from 5 percent up; in some cases, to as high as 90 percent.

In the case of the water treatment processes, about the same thing seems to hold.

Generally speaking, the existing water treatment processes will remove only from perhaps 30 to 40 percent to perhaps as high as 95 percent of the radioactivity in the water supplies. The variation in percentage depends on the specific nature of the isotope that is involved. So that, as a general conclusion, I think one would have to say that the effectiveness of existing water treatment processes in sewage treatment plants for most of the wastes that we are talking about is rather limited.

Representative PRICE. That is all I have.

Representative HOLIFIELD. Mr. Bates.

Representative BATES. Who did you say made these samples to see whether or not these were within the allowable limits? Who actually made the samples?

Dr. LIEBERMAN. We had the Geological Survey taking some samples, the General Electric Co., that is, the Knolls Atomic Power Laboratory, took some samples, the Harvard University people who we had up there took samples, and the State health department took samples, and the results of analyses and so forth were interchanged.

In other words, we wanted to make sure that everybody who had an interest in this was completely involved and completely integrated in this whole study. As a matter of fact, this example I think

is one that is useful in pointing out the thing that I mentioned earlier, it gave us an opportunity to get the people in the State cognizant of some of the activities in this field and to develop a competency within their own organization.

Representative BATES. I was trying to determine whose responsibility it is at the present time to follow these things through and police them?

Dr. LIEBERMAN. The responsibility at the present time ultimately is that of the AEC. At the same time, we do enjoy at the Knolls Atomic Power Laboratory a very nice working relationship with the State health department, and although I am not familiar with their detailed operations, I feel quite sure that the State health department periodically goes out and collects samples themselves and sees what they have.

Representative BATES. Apparently they did the development for it.

Dr. LIEBERMAN. Yes.

Representative BATES. And also, the Public Health Service, but I wanted to know whose responsibility it was and whether or not AEC was letting go of this thing before someone else is actually assuming the full responsibility.

Dr. LIEBERMAN. No, sir. I can say categorically here that the AEC in its operating contract at the Knolls Atomic Power Laboratory is ultimately responsible for the adequate, safe management of the waste from that installation.

Representative BATES. But eventually you will turn it over to some other agency, whether it is the U.S. Public Health Service, or State or combination of both?

Dr. LIEBERMAN. This, sir, gets into another question that I think will probably be discussed at a later set of hearings, where the relationship between Federal and State and other agencies will be discussed. I think that I would rather defer any comments on that to those hearings.

Representative BATES. I wondered now about the dissemination of information that we might uncover in our own laboratories. Is that all disseminated to the people who might be interested in it as far as this disposal is concerned?

Dr. LIEBERMAN. We certainly feel it is disseminated to the working people in the field. The dissemination of information is a problem to itself. Some people feel that if we would cut down on the amount of papers being distributed, we would be better off.

Representative BATES. It depends on what you say.

Dr. LIEBERMAN. That is precisely the case; it depends on what you say.

My own personal view is that dissemination of this information, because it is almost entirely unclassified, is quite good.

Representative BATES. How about the situation particularly in some of these plants that were financed to a large degree by the Government? I presume that they are going to learn a lot from experience, and how about that experience? Is that to be relayed to AEC and disseminated to other interested parties?

Dr. LIEBERMAN. Certainly, sir, it has been my experience that in any plant or any installation where the AEC has an interest, the

information developed has been made available to anybody that has an interest in this.

Representative BATES. That is all, Mr. Chairman.

Representative HOLIFIELD. I might say that the Atomic Energy Act of 1954, as amended, places the basic responsibility in the AEC for the ownership of radioactive materials, the custody of it, following it to place of use, that all of the contracts of the AEC with private industry have an interchange of information which makes it obligatory upon the part of the private industry to follow the rules and regulations in regard to health and safety, and also to exchange any information or techniques that are developed either on the part of private industry or the AEC.

When it comes to the radiation, which goes beyond that of atomic energy material, then there are certain State laws which have to do with X-ray equipment, fluoroscopes, and all that sort of thing, which take care of the field which the AEC is not by statute obliged to take care of.

There is a growing feeling that there has to be a coordination between the different fields, the fields outside of the Atomic Energy Commission's responsibilities and the other fields, and that is why the Council of Governors and other groups that are interested in the wide field are having different conferences and are trying to evolve model legislation which will coordinate with the Atomic Energy Commission this field of responsibility to the public on health and safety. This committee's obligation will carry forward as far as retaining jurisdictional control over the statutes which impose responsibility upon the AEC, regardless of what happens in the State, and I am sure that this committee, in the discharge of its duty, will not allow the AEC from a statutory standpoint to relinquish its responsibility into incompetent or uninformed hands, and as soon as competence can be developed on the local political levels, I am also sure that this committee and the Commission will be perfectly willing to relinquish it.

The overall responsibility of the safety of the public still remains in the AEC and in this committee legislatively.

Chairman DURHAM. I fully agree with you on your statement. I think I would carry it a little bit further.

Since, of course, Dr. Lieberman has had quite a bit of experience in the operation of the present program, I wonder if you would comment on it, as to whether or not it would be better for the State to adopt a code of ethics something similar to the State of Pennsylvania, rather than trying to adopt anemic laws, that operate on a basis closely with the public health people of the States which all have public health setups.

Dr. LIEBERMAN. I would like to answer that, if I may, Mr. Durham, on the basis of my own personal experience.

Chairman DURHAM. That is the reason I asked the question.

Dr. LIEBERMAN. We have enjoyed, I think, a very excellent working relationship with people in the various States who have a direct interest and concern in this waste business. These jurisdictional questions have come up. I think it is a credit to these people in the States that we were able to say, "Well, let's not worry about the jurisdictional question. Let's get a job done."

Chairman DURHAM. I think you are right on that.

Dr. LIEBERMAN. This whole question of who should have jurisdiction I feel that I personally am not competent to answer certainly. I have some personal opinions on the matter. I would agree with Mr. Holifield in saying that I certainly would not want to see the responsibility for the health and safety of the public fall into incompetent hands, and I certainly think there has to be some kind of coordination and integration of the requirements, the laws that govern these things.

I think that—again I am speaking from a personal point of view—it would be mistake to have perhaps 48, 49, or 50 different sets of regulations that might tend to confuse the situation. But from the technical standpoint, and this is the standpoint that I would rather talk from, I don't feel that there has been any kind of problem that has arisen that we haven't been able to tackle on a good working relationship with the technical people involved.

I don't mean to be facetious, but I would let the lawyers worry about who has the jurisdictional responsibility later.

Chairman DURHAM. The question, of course, is very important in developing the competence and good administration. It is a dangerous program if it is not carried out in its proper manner.

Of course, at the present time it so happens that the AEC has in its progress and development—certainly with good competence I believe—a program to protect the safety of the American people.

I remember the question this morning as to whether or not we are going to have a checkerboard situation, but I am concerned about it, and that is not good, I believe, administration of such a program.

Representative WESTLAND. Doctor, is it safe to say that under the present program of the dispersal of these waste materials, the public health is not being endangered in any way?

Dr. LIEBERMAN. Yes, sir; on the basis of the testimony that was given this morning and my own personal feeling, I think that is a safe statement.

Representative WESTLAND. That is all.

Representative HOLIFIELD. Mr. Toll.

Mr. TOLL. Dr. Lieberman, during the noon hour a representative of the Harris County Health Unit of Harris, Tex., visited the offices of the Joint Committee and spoke with the committee staff. And as I understand it, there is a dispute in that area over a proposed action of the AEC, to issue a license to an organization to dispose of waste in the Gulf of Mexico.

Could you comment at this time and perhaps supply more detailed information for the record later as to the nature of the wastes involved in that proceeding and the present status of that case?

Dr. LIEBERMAN. Yes, I can, Mr. Toll.

The first thing I would want to say in this connection is to make sure that we understand the kinds of wastes that are involved. These are low-level solid or packaged wastes with relatively small quantities of radioactive materials that are proposed for disposal at a specific location in the gulf.

In connection with all of these sea-disposal operations we went to the National Academy of Sciences, to their committee on oceanography, and asked them to take a good look at the feasibility of establish-

ing designated areas, both along the Atlantic coast and the gulf, and they have another group working on the Pacific coast, for disposal of this kind of waste. And I have to emphasize "this," because in almost every case where we have had these discussions, the next thing I know somebody talks about disposing of the high-level wastes in the ocean, so I want to emphasize this point.

I am not familiar with all the details of the license application, but certainly from the technical review of the situation and our consultation with the various experts in the marine sciences, it looks like with the quantity of waste involved—as I recall the maximum possession limit for this particular license was something like 50 curies, I am not exactly sure of the number, but it was that order of magnitude—this quantity of that kind of radioactivity could be disposed of at that location safely.

We did meet with representatives of the Texas State Health Department and other State people in Austin last week and then some of the other representatives of the AEC went on down to Houston for a public hearing in this connection. I wasn't at the hearing and therefore cannot comment directly, but from a technical standpoint this group of experts, these marine scientists, have concluded that certain—I think there are about 25—specific locations along the Atlantic and gulf coasts could be set up for certain quantities of this kind of radioactive waste which could be disposed in these areas and be done safely.

The report of this committee is, I think, essentially completed and we should be getting it any day now.

Mr. TOLL. The chairman of the subcommittee has told representatives of Harris County that they may file a statement for the record in these proceedings and it might be helpful if the AEC would also submit any further technical data that you have on this particular case.

Dr. LIEBERMAN. Yes, sir; I am sure that the record of the hearings held at Houston can be made available for the committee at any time. The technical aspects of the situation were covered in considerable detail at those hearings.

(The Harris County statement, a letter from Harold L. Price, and the Intermediate Decision referred to appears on p. 3043.)

Representative HOLIFIELD. The people around Houston are quite sensitive about this since the incident that occurred there a year or so ago in the escape of that material that contaminated some of the workers and was carried into their trailers.

Dr. LIEBERMAN. Yes, sir. If I might be permitted an additional statement in this regard, Mr. Holifield, an analogous situation, as you know, took place in the State of California last summer or last fall.

It is my own feeling that much of the apprehension can be laid at the door of lack of information by the public in general.

Representative HOLIFIELD. That is right. That is another reason why we are having these hearings, to bring this information out as we did in the radiation fallout hearings, to bring it into one place, so that people who are concerned with this problem can study the testimony of experts.

Thank you very much, Dr. Lieberman.

We will have at this time as witnesses Dr. Harold A. Thomas, of Harvard, and Dr. R. F. Foster, of Hanford.

I believe you, Dr. Thomas, will be the first witness. We are happy to have you. You may proceed.

STATEMENT OF HAROLD A. THOMAS, JR.,[6] PROFESSOR OF CIVIL AND SANITARY ENGINEERING, HARVARD UNIVERSITY, ACCOMPANIED BY FRANK PARKER, OAK RIDGE, TENN.

Mr. THOMAS. Mr. Chairman, the airplane has interrupted my hearing a little bit and I have asked Dr. Frank Parker, of Oak Ridge, Tenn., to second his former professor here.

Representative HOLIFIELD. All right.

Mr. THOMAS. Dr. Parker has had intimate connection with the research I report.

First, sir, I would like to make a point that I believe all the assembled experts here would have me make, that when we talk about the disposal of low-level liquid radioactive wastes in surface waterways, we are talking at best about an extremely tiny fraction of the total projected production of wastes, a very small amount, that at best can be handled.

In the document I have listed the sources of low-level wastes. Other witnesses have covered these and I will not elaborate.

Representative HOLIFIELD. We would appreciate it if you would summarize. There does seem to be quite a bit of repetition in this testimony, so if you can go through, Dr. Thomas, and summarize or at least take the important parts of your testimony, we will print the whole testimony in the hearing for the record.

Mr. THOMAS. Very well. The only point I wish to stress with the low-level wastes is that one potential source of these, in addition to legitimate sources from the atomic energy industry, is that they may be expected to enter waterways as a result of accidents, or inadvertent discharges or leakage, or temporary breakdowns in other methods of waste disposal.

When these radioactive wastes are released in rivers and streams, natural processes operate to disperse them and remove them, wholly or in part, from the flowing stream. Collectively, these processes are called self-purification. Since this process is somewhat of a mystery to the layman, I have elaborated on it a little bit here and the highlights are essentially these. In conjunction with the physical dispersion and dilution that occur by mixing, there are certain important chemical and biochemical actions that are brought about by aquatic

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S.B. (Carnegie Institute of Technology), 1935; S.M. in sanitary engineering (Harvard University), 1937; S.D. (ibid.), 1938. Assistant in sanitary engineering, 1935–37; instructure in sanitary engineering, 1938–41; faculty instructor in sanitary engineering, 1941–44; assistant professor of sanitary engineering, 1944–47; associate professor of sanitary engineering, 1947–56; Gordon McKay professor of civil and sanitary engineering, 1956—; Harvard University.

Member: American Society of Civil Engineers, American Academy of Arts and Sciences, American Geophysical Union, Federation of Sewage and Industrial Wastes Associations.

Principal research has been related to fluid mechanics and hydrological problems having sanitary engineering application, particularly in treatment plant design and stream sanitation. Concerned for the past ten years with problems involved in the disposal of radioactive wastes in streams and ground water, Professor Thomas has been director of an AEC-sponsored research project in the field at Harvard since 1950. He is also a consultant to the Sanitary Engineering Center of the U.S. Public Health Service and to the Department of Defense (1952–58). Member since 1944 of the Subcommittee on Waste Disposal, Committee on Sanitary Engineering and Environment, of the Division of Medical Sciences, National Research Council, Washington, D.C.

plants and animals, by sunlight, and by the hydraulic agitation of the stream. These mechanisms tend to purify the water by chemical precipitation, agglomeration, settling action, and biological uptake of organisms.

In addition to these effects, the stream of course provides time for radioactive decay and free transportation to the ocean.

The inherent ability of the stream to purify itself is a potent natural force and in the industrial complex of the Nation is a most valuable resource. In the document I have elaborated on the evolution of our modern water carriage system, and the essence is that (on p. 3 there), in terms of economics, the engineering problem arising with the occurrence of a new class of noxious wastes by this industry we are talking about is simply to distribute the capital investment in an optimal combination of treatment plants which, together with natural purification, accomplish the desired objective.

One can't talk about river disposal without talking about the complex of treatment plants and the river regulating structures, and it is manifest that a research program such as ours, which investigates capacity of surface waters for the safe disposal of these wastes, must take into consideration the close interrelationships and complementarities that exist between artificial and natural treatment.

As to the project itself, a series of investigations have been made since 1951 in a contract with the Reactor Division of the AEC to assess the feasibility of the disposal of certain low-level wastes in streams. Most of the experiments have been conducted on Cochichewick Brook near Lawrence, Mass., and have been done in cooperation with the State Health Department. This brook is a privately owned and controlled stream and is ideal for test purposes, in part because it has a large body of water from which it draws and has uniform flows during the years.

The technical details have been outlined, the sizes of the stream and the sampling program, and I don't think we need to go into that. In simple language, what we have been doing with this stream is to take small and safe amounts of radioactive isotopes of the types listed; strontium, zirconium, ruthenium, cesium, rubidium, cerium, and some of the rare earths, and dose them into the stream and trace their fate as they progress down to the Merrimack River and thence to the sea.

The important point is that the results indicate a wide range of self-purification. In some runs with certain isotopes, for example, radiophosphorous, we get nearly 100 percent removal in our test. It disappears from the flowing water. In other cases, maybe nothing is removed.

A large number of factors affect the removal, such as the time of the year, the temperature, the presence or absence of ice cover, the density of algae, the amount of carrier added: all these many factors mean that we have to treat the data statistically. I have made some mention of correlation coefficients in the document, and the upshot of the work is in many cases, despite the work we have done, it is pretty hard to predict in a given situation what the results of a given run will be.

In collateral tests in the laboratory on artificial streams, we can control conditions better and (as indicated on page 6) we do get a

stronger correlation coefficient between the self-purification of pollutional load capacity and these important environmental factors.

I should like to emphasize that one of the important factors of this field investigation has been the study of the hydraulic mixing dispersion process in the stream. It is an important factor. It materially affects the capacity of the stream for handling pollution and has received relatively little attention in the past.

We have had the enthusiastic support of the AEC Reactor Division people in going into this study and the work at Harvard, together. with similar work at Northwestern University and Johns Hopkins has resulted in scientific contributions to fluid mechanics and limnology.

I have outlined here the work done along these lines by Dr. Bell at Northwestern University, AEC-sponsored work. A particularly interesting feature of the Northwestern study was the measurement of mixing characteristics in the Vicksburg, Mississippi River model of the Corps of Engineers.

I have also included in the document information pertaining to these tests on the Mohawk River, which have been discussed by Dr. Lieberman. There is no need at this point to elaborate on that. He has covered the most significant results.

On page 8, I summarize the most significant findings of our work in the past 7 years and the work at other research centers of a similar nature. There are seven points.

The first point is that under favorable conditions, at many sites, it is reasonable to expect that substantial amounts of low-level wastes of several types may safely be discharged into inland waterways, and such discharge may be more economical than other methods of handling diluted waste and may entail negligible public health hazards.

The second point: It is to be emphasized that the dispersion and self-purification process does not destroy the radioisotopes. At most they are diluted down to safe levels or transferred from the flowing water to the stream bed or to aquatic plants and animals. The latter may concentrate the activity to a marked degree.

The third point: This is a point of considerable scientific engineering interest—is that the uptake of the radioisotopes on the stream bed has been found to depend critically on the amounts of nonradioactive elements of the same or similar chemical species that happen to be present in the waste stream or purposely added or occur antecedently in the water wastes.

The fourth point: Some isotopes, such as rubidium 86 and iodine 131, may not be removed in significant amounts for the flowing water and do not collect on the bottom or concentrate in living organisms.

It has been found, however, that self-purification in the stream may so alter the physical and chemical form of these limits so that in passage downstream they are rendered more amenable to treatment in water-processing plants.

Fifth, and, sir, this is the major point, the storage of long-lived radioisotopes absorbed or deposited on the stream bed must be regarded as precarious and unreliable. Sudden release from bottom storage of hazardous isotopes such as strontium can occur during unusual stream conditions such as floods and droughts. A particu-

larly dangerous situation could develop during a severe warm weather drought, at which time the entire stream flow may be pumped to municipal use. In this situation, it is conceivable that many years of accumulation of long-lived nuclides may be released from bottom storage with the upset of the normal biological and chemical balance. The release could occur abruptly with the flotation of old organic bottom deposits buoyed upward by gaseous fermentation. It is manifest that a satisfactory monitoring and stream survey program must include periodic inventories of long-lived activity stored in bottom deposits.

Six, the hydraulic mixing and dispersion action in some waterways may be extremely erratic and exhibit markedly different patterns at different times. Under conditions of low flow and wind and with large vertical temperature gradients, very little mixing and dilution of the waste stream may occur during many miles of downstream travel.

Sampling programs should be planned carefully on the basis of detailed knowledge of the hydraulic mixing characteristics of the stream. Moreover, they should be designed primarily to indicate the concentration and amount of activity that is withdrawn at points of use.

I think this can hardly be overemphasized. Our test results show decisively that in a natural stream, subject to the vagaries of the weather, careful measurements of the amounts of activity entering the stream do not in themselves supply us sufficient information to safely predict the amount of activity that will be pumped at a downstream water intake.

The seventh and last point is simply that the extent of which our surface waterways can safely be used in this disposal of low-level wastes is, as I said, limited to a minute fraction of the entire production of waste projected in the future.

I have included some computations concerning this which I hope are comprehensible to the layman. The import of these is simply that, for example, in the year 1990 the amount of waste, if we take one isotope, strontium 90, that will be produced, will be something like 10,000 or 100,000 times more than we could possibly discharge in our streams if we loaded all the surface water in the country up to the strontium tolerance level. Of course by 1990 our concern is not just the amount that we will have produced in that year, but it will be the accumulated amounts which might be in the order of possibly 10 to 9 or possibly 10 to 10 curies.

I don't want to elaborate on this well-known numbers game, but simply to say it is evident that these enormous amounts of activity relative to what we could possible handle safely in our waterways will have to be processed or transferred to storage in a very carefully administered routine which leaves very little margin for errors or accidents that might damage our waterways.

In closing, sir, I would like to acknowledge here the very helpful support and close cooperation of the people in the Reactor Division, particularly Dr. Lieberman and Mr. Arthur Gorman.

(Prepared statement of Mr. Thomas follows:)

Disposal of Low Level Liquid Radioactive Wastes in Surface Waterways

(By Harold A. Thomas, Jr., Gordon McKay, professor of civil and sanitary engineering, Harvard University, Cambridge, Mass.)

Low level liquid radioactive wastes are produced in several ways. In the atomic power industry they derive from ore mining and processing, from washing, cleaning and decontamination operations at reactors and chemical reprocessing plants, from the treatment of coolant water, and from waste storage tanks after detention for radioactive decay. They also occur in the waste water from laboratories, hospitals, and industries using or processing fission products. Finally, they may be expected to enter waterways as a result of accidents or inadvertent discharges and leakage and of temporary breakdowns in other methods of radioactive waste disposal.

When liquid radioactive wastes are released in rivers and lakes various natural processes operate to disperse them and to remove them wholly, or in part, from the flowing water. Collectively these processes are called stream self-purification. In conjunction with the physical dispersion and dilution of the waste stream, important chemical and physical changes may be brought about by hosts of aquatic plants and animals, by other chemical compounds in the stream, by sunlight, and by the hydraulic agitation and mixing of the stream. The mechanisms that tend to purify the water include chemical precipitation, agglomeration of particles, deposition by gravity, absorption on the streambed and biological uptake by aquatic organisms. In addition to these effects the stream provides time for radioactive decay and free transportation to the ocean.

The inherent ability of a stream to purge itself of pollution is a potent natural force and in the industrial complex of this Nation is a valuable natural resource. In order to convey an insight as to the function of stream self-purification in industrial radioactive waste disposal, it is pertinent to outline briefly the evolution of our present-day water-carriage system for handling waste materials.

The water-carriage system of waste disposal is a development of western culture that is quite as essential to modern industrialized society as are the wheel and the alphabet. Good municipal drainage has been a prerequisite for healthy urban life since the time of the early city-states on the Euphrates and Nile Rivers. One of the principal achievements of the sanitary revolution in the 19th century in this country and in other western nations was the renascence and elaboration of the water-carriage system for the disposal of municipal sewage. The main lines of sanitary engineering effort in the present century have been directed toward improving and extending its utility particularly in the handling of ever-increasing quantities of industrial wastes of many types.

Formerly a sewerage system was considered adequate if it just provided collection lines so that the raw waste could be dumped into the nearest convenient stream. As a result of this practice in the early years of this century an increasing number of our cities and towns were compelled to build water purification plants in order to secure a potable water supply. This happened in river basins where because of population density or other reasons stream self-purification was insufficient by itself to handle the waste load. More recently, with the continued increase in population and progress of industry, at many places it has been necessary to add a third line of defense—the waste treatment plant—at the end of the collection system. However, despite the huge investment in treatment plants that we have made and must continue to make, stream self-purification remains a most important natural force that must be properly integrated in our economy. It has been estimated that at the present time the average cost of water treatment for domestic and industrial use in many of our major cities would have to be increased by a factor of 10 or more if it were not possible to rely on stream self-purification to reduce the pollution load from upstream sources. An engineering problem of cardinal importance is the design of water and waste-water treatment plants as well as storage dams and other structures that affect the natural stream regime so as to utilize the self-purification capacity of our waterways in a manner consonant with other stream uses.

In terms of economics the engineering problem that arises with production of a new class of noxious liquid wastes produced by the atomic energy industry is to distribute capital investment in an optimal combination of properly scaled treatment plants and river regulating structures as to meet the hygienic and esthetic requirements of safe and palatable water supplies. Other objectives

must also be met such as the protection of recreational areas, ice supplies, shellfish layings and other aquatic life that may have value economically or to the sportsman.

It is manifest that a research program investigating the capacity of surface waterways for the safe disposal of radioactive wastes should take into consideration the close interrelationships and complementarities existing between artificial and natural purification. The use of the stream for waste disposal must also be reconciled with other economically important stream uses.

A series of investigations at Harvard University since 1951 in a contract with the AEC Reactor Division have been made to assess the feasibility of disposal of low level liquid radioactive wastes in streams. Most of the experiments have been on Cochichewick Brook near Lawrence, Mass.; other streams and reservoirs have been used in special tests. The work has been done in cooperation with the Sanitary Engineering Division of the Massachusetts State Department of Public Health. Cochichewick Brook is a small stream that is privately owned and controlled. It has several mill ponds and originates in a large body of water, Lake Cochichewick, which supplies water to the town of North Andover, Mass. Several factories use the stream for process water. However, the waste streams from these industries are small and do not affect the stream water quality significantly throughout the test reach. With the large volume of Lake Cochichewick available for regulation, the stream is maintained at a fairly constant rate of flow throughout the year.

The standard test procedure has been to inject doses of various radiosotopes at biweekly or monthly intervals and to trace the progress of the pollutant 1.5 miles downstream past seven sampling stations to the junction of Cochichewick Brook and the Merrimack River. Automatic sampling devices operate at stations 6 and 8; these collect one liter samples of stream water at 2 hour intervals continuously during the test. The run normally takes from 2 to 5 days depending on hydrological conditions. The volumes of the stream and its two principal impoundments are indicated in the following table:

Station	Volume in reach, cubic feet	Mean flow time, days (at 5 cubic feet per second)
3 dosing point.		
6 sampling point	135,000	0.31
8 sampling point	716,500	1.66
Total	851,500	1.97

The flow rate varies from 3 to 15 cubic feet per second; most of the time range is 5 to 8 cubic feet per second. Tests have been made with several isotopes such as radioiodine and radiophosphorus and important fission products including strontium, zirconium, ruthenium, cesium, rubidium, cerium, and promethium. These have been dosed with and without carriers—nonradioactive elements of the same chemical species. The amounts of activity that have been added vary from 25 to 100 millicuries.

The results indicate a wide range in the degree of self-purification. With radiophosphorous, in some runs, less than 5 percent of the initial slug was found to pass the terminal downstream station; with rubidium, often no removal occurs. With a given isotope the efficacy of self-purification has been found to vary considerably with the volume of streamflow, temperature, season of the year, presence or absence of ice cover, density of algae in the stream, amount of carrier added with the dose, and wind direction and magnitude. Due to the effect of these many factors, it has been necessary to employ statistical techniques in processing the data. Correlation coefficients between the degree of self-purification and the other environmental factors have been obtained. The correlation coefficients have been found generally to be low, and for some isotopes it is difficult to predict accurately on a given run what the result will be. In collateral tests on artificial streams and basins in the laboratory where hydrographic conditions may be controlled more closely, stronger correlation coefficients have been obtained, and the more important environmental factors

identified. In the laboratory it is possible to demonstrate the marked effect of streamflow rate on self-purification. At low rates the dilution is small but flow-times are large and biochemical and chemical activity may effectively reduce the high concentrations of pollutant; during periods of high flow rates the relatively large dilution afforded may be offset by the shorter flow-times available for self-purification and decay.

Of particular interest in the field investigations, has been the study of the hydraulic mixing and dispersion process as induced by currents, by winds and by temperature gradients. This is an important factor that materially affects the capacity of streams for handling pollution This factor has received relatively little attention in the past. The extent to which longitudinal mixing can reduce the concentration of a slug of concentrated activity in the downstream passage to the sea is an important consideration in assessing hazards from accidental releases of high level wastes. An understanding of the mechanism of lateral, longitudinal, and vertical mixing of wastes in waterways is necessary in planning the sampling programs and monitoring schedules at water intakes. Radioactive tracers are an ideal tool for investigating the hydraulic dispersion process and substantial contributions to the sciences of fluid mechanics, limnology and rheology have resulted from the Harvard studies and from similar AEC sponsored investigations by Bell at Northwestern University, by Geyer and Bryant at Johns Hopkins University, and by workers at other research centers.

Valuable information pertaining to the movement and ultimate fate of fission products in waterways has been obtained from radioactive fallout from nuclear weapons tests. Isotopes from fallout have been found to exhibit a behavior similar to those introduced in our test program. The fallout, however, has not been an unmixed blessing. At times it has been difficult to coordinate the test schedule with the weapons detonation program. Also, the erratic occurrence of fallout has necessitated maintenance of an elaborate sampling program of rainfall and of control points to assay fallout activity.

Similar stream investigations by Bell at Northwestern have yielded important results bearing on the receptivity for radioactive wastes of the Illinois River system and the Chicago drainage canal. In this work an attempt has been made to relate retentions of several isotopes simultaneously injected to one material reflecting the mechanical fate of the injected mixture alone. The tests have been made both during normal stream flow conditions and under warm-weather drought conditions. A particularly interesting phase of this program has been the measurement of longitudinal mixing of radiotracers in the Vicksburg Mississippi River Model of the Corps of Engineers.

Reference should also be made to a successful series of large-scale tracer tests in the Mohawk below the sewer outfall of the Knolls atomic power laboratory. These tests were undertaken at the instigation of the AEC Reactor Division and were carried out in a joint project by the United States Geological Survey, the KAPL Health Physics Division, the New York State Department of Public Health, and the Harvard group. The objectives of the tests were to assess the health hazards associated with accidental spillage of radiocontaminants and to ascertain the amounts of certain low-level wastes that might safely be discharged to the Mohawk River. Of particular concern in this connection is the existence of a water supply intake for the town of Cohoes, N.Y., on the Mohawk River just upstream from the junction with the Hudson River. The tests which were similar in plan to those previously described, indicated quite a substantial degree of dilution and self-purification for certain isotopes. In one run in which 4.5 curies of radiophosphorous were dosed at the outfall, it was found that 97 percent of the activity was removed by self-purification from the flowing water in travel down to the Cohoes water intake. An interesting result from the test series were measurements indicating the degree of absorption of activity in the vicinity of the dosing point.. The rate of dispersion was found to be markedly dependent upon temperature differences between the waste and the river. An agreement based on these tests was reached between KAPL and the New York State Health Department as to permissible levels of activity discharge and as to details of monitoring and routine stream surveying.

In summing up the most significant findings to date of investigations of the disposal of radioactive wastes in surface waterways, the following points may be made.

1. Under favorable conditions prevailing at certain sites it is reasonable to expect that substantial amounts of low level wastes of several types may be safely discharged to inland waterways. Such discharge may be much more economical than other methods of handling dilute wastes and entail negligible public health hazards.

2. It must be emphasized that in the dispersion and self-purification process the radionuclides are not destroyed; at most they are diluted to safe levels or transferred from the flowing water to the stream bed or to aquatic plants and animals. The latter may concentrate radioactivity to a marked degree.

3. The uptake of radioisotopes on the stream bed has been found to depend critically upon the amounts of nonradioactive elements of the same or similar chemical species that are present in the waste stream or exist antecedently in the waterway.

4. Some isotopes, such as rubidium 86 and iodine 131, may not be removed in significant amounts from the flowing water and do not collect on the bottom or concentrate in living organisms. It has been found, however, that self-purification may alter the physical or chemical form of these elements so that in passage downstream they may be rendered more amenable to treatment in water-processing plants.

5. The storage of long-lived radioisotopes absorbed or deposited on the streambed must be regarded as precarious and unreliable. Sudden release from bottom storage of hazardous isotopes such as strontium can occur during unusual stream conditions such as floods and droughts. A particularly dangerous situation could develop during a severe warm-weather drought at which time the entire streamflow may be pumped to municipal use. In this situation it is conceivable that many years of accumulation of long-lived nuclides may be released from bottom storage with the upset of the normal biological and chemical balance. The release could occur abruptly with the flotation of old organic bottom deposits buoyed upward by gaseous fermentations. It is manifest that a satisfactory monitoring and stream survey program must include periodic inventories of long-lived activity stored in bottom deposits.

6. The hydraulic mixing and dispersion action in some waterways may be extremely erratic and exhibit markedly different patterns at different times. Under conditions of low flow and wind and with large vertical temperature gradients, very little mixing and dilution of the waste stream may occur during many miles of downstream travel. Sampling programs should be planned carefully on the basis of detailed knowledge of the hydraulic mixing characteristics of the stream. Moreover, they should be designed primarily to indicate the concentration and amount of activity that is withdrawn at points of use. Our test results decisively indicate that with a natural stream, subject to the vagaries of the weather, careful measurements of the amounts of activity discharged into the stream do not supply sufficient information to use in estimating the amount of activity that will be pumped at a downstream water intake.

In the past there has been an abundance of water in most parts of the country but now a condition of growing scarcity is developing. As has been stated a common practice of disposal of waste waters has been to return them to the stream system from which they were withdrawn—either with or without treatment. As the waste water flows to the ocean it may be recaptured and reused several times. The extent of reuse on some of our major streams has increased greatly since 1940 and many water treatment plants now have difficulty in meeting quality standards. The extent to which our surface waterways can safely be used in the disposal of radioactive wastes is limited to a minute fraction of entire production of radioactive wastes that is projected in the years ahead. For example, the total permissible load of strontium 90 that could be carried in the surface runoff of the entire country during any year using the maximum permissible concentration of 10^{-7} curies per cubic meter amounts to about 1.6 by 10^6 curies. Projected figures for the production of strontium 90 in the year 1990 in power reactors installed in the United States at that time, range from 10^8 to 10^9 curies. By 1990 it is anticipated that cumulative amounts of strontium 90 produced will range from 10^9 to 10^{10} curies. These enormous amounts of activity will have to be processed or transferred to storage in a carefully administered routine in which there will be little margin for errors and accidents that might damage our inland waterways.

It is manifest that water will become increasingly a major factor in the planning of industrial and public works; integrated water conservation schemes for multipurpose use will be needed on a large scale in the years immediately ahead.

In closing, it is appropriate to acknowledge for the Harvard surface water project the helpful support and cooperation of Mr. Arthur E. Gorman and Dr. Joseph A. Lieberman of the AEC Division of Reactor Development.

Representative HOLIFIELD. Thank you, sir.

Are there any questions of Dr. Thomas?

Do you have anything to add, Dr. Parker?

Dr. PARKER. No, sir.

Chairman DURHAM. Doctor, what you say, that dilution at the present time of the waste material that is coming from industrial setups throughout the country creates a much larger problem. We certainly cannot do without water in this country.

Mr. THOMAS. Sir, one thing that Congress should appreciate is that a very sizable proportion of our technical competency in waste disposal technology is assembled right in this room. This technology has become more difficult and we are spread kind of thin at the present time, and I believe it is important that Congress understands that sanitary engineering and other forms of expertise that entail tracing waste in nature are a product of this country and they do not exist to any appreciable extent in the foreign countries.

Chairman DURHAM. We are actually not keeping up with it at the present time, as you point out in your statement.

Mr. THOMAS. No, I don't say that. I just say it is a difficult task.

Representative HOLIFIELD. You have well said that a great deal of the information on this subject is assembled here in the minds of the people that have had the most experience in this room and this is one of the reasons why we want to put this in writing, so that this in printed form can be accessible to all of the States and all of the public health bodies throughout the Nation, and throughout the world as far as that is concerned, because this is international as well as a national problem, and this will help in the realization of the problem and may be some encouragement towards training the right kind of people in the different areas where these problems are going to be prevalent.

Chairman DURHAM. I just hope and also pray that we will not have to use our streams for this, because I know it does create a problem, as your study has already proved.

Mr. THOMAS. We have other important uses for these streams.

Chairman DURHAM. Yes, indeed.

Representative HOLIFIELD. We certainly do.

If there are no further questions of Dr. Thomas, we will excuse you, sir, and thank you, and ask Dr. Foster of Hanford to come to the witness stand.

STATEMENT OF R. F. FOSTER,[7] MANAGER, AQUATIC BIOLOGY, HANFORD LABORATORIES, HANFORD ATOMIC PRODUCTS OPERATION, GENERAL ELECTRIC CO.

Dr. FOSTER. Thank you, Mr. Chairman.

My name is R. F. Foster. I am employed by the General Electric Co. at the Hanford atomic products operation in Richland, Wash., as manager of aquatic biology in the Hanford Laboratories Operation.

My remarks are intended to provide a résumé of the research and development work at Hanford which relates to the disposal of radioactive waste to the Columbia River. Much of this work is so closely associated with plant operation that it could have been considered under the topic of waste management. Indeed, a close liaison exists between the manufacturing components and the research teams which allows immediate application of new information on the one hand and rapid investigation of new problems on the other.

Waste disposal to surface waterways creates a number of problems which are common to the disposal of wastes in other types of environments as well. For surface waterways, however, it will usually be possible to predict or measure the concentration and time and place of arrival of the waste with an accuracy which is not common to disposal in the ocean, atmosphere, or ground.

An abundance of water is available in the Columbia River for dilution of the effluent from the reactors. By itself, however, this fact is not sufficient to define the exposure to water users downstream or to the aquatic organisms. It must be supplemented with observations on how completely and how quickly the effluent becomes mixed with the river water, how much of the radioactivity is retained by the river sediments, and how much is accumulated by fish and other aquatic organisms.

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Marital status: Married. Number of dependents: 3.
Education: University of Washington; B.S. Fisheries, 1938; Ph.D. Fisheries, 1948.
Technical adviser, U.S. delegation, peaceful uses of atomic energy, Geneva, 1955.
Participant, symposium on marine biological applications of radioisotope research techniques, Naples, 1957.
Special lecture in fisheries, University of Washington, 1952, 1954, 1959.

WORK HISTORY

1938–41: Teaching fellow, Department of Fisheries, University of Washington, Seattle.
1942–43: Biologist, Washington State Pollution Commission.
1943–45: Research associate, applied fisheries laboratory, University of Washington.
1945 to present: Manager, aquatic biology, Hanford Laboratories (various similar titles were used in earlier organizational structures); General Electric Co. (in 1945 the E. I. duPont Co.), Richland, Wash.

PROFESSIONAL SOCIETIES

Member, American Fisheries Society; the Wildlife Society; American Society of Ichthyologists and Herpetologists; AAAS; AIBS; Pacific Fishery Biologists; Radiation Research Society; Pacific Northwest Sewage & Industrial Wastes Association.

COMMITTEE MEMBERSHIPS

Member, Committee on Effects of Atomic Radiation on Oceanography and Fisheries, National Academy of Sciences Study of the Biological Effects of Atomic Radiation.
Member, nuclear wastes committee, American Federation of Sewage & Industrial Wastes Associations.
Member, industrial wastes committee, Pacific Northwest Sewage & Industrial Wastes Association.

Several surveys have been made to map the distribution of the effluent in the Columbia River and to determine the length of time required for the effluent to travel to points of water use under various hydrographical and operational conditions.

Figure 1 (p. 1021) illustrates the type of information which is obtained. The results of these surveys have been of value not only for the estimation of radiation exposure but also as a guide in the selection of reactor sites.

While the gross radioactivity of the reactor effluent at various points of interest can be measured by compartively simple counting techniques, such measurements are not sufficient to define the exposure with the required accuracy. The reactor effluent contains many different radioisotopes—this was mentioned by Dr. Parker yesterday—and the contribution which each of these makes to the overall exposure changes according to how the water is used, such as for drinking, swimming, boating, industry, irrigation, or production of fish and wildlife.

Further, the most abundant radioisotopes are not necessarily the ones which present the greatest radiological problem. The need to identify and measure the individual isotopes present in reactor-effluent water has resulted in the development of analytical methods which are capable of measuring extremely small quantities of the isotopes. Adaption of electronic instruments to the routine analysis of reactor-effluent water has also resulted in substantial savings in manpower, and in the length of time required to process the samples.

Developmental work in instrumental analysis is still being carried forward. One objective is to perfect a waste-stream monitor which will automatically detect, measure, and record the concentration of individual isotopes of special interest. Such an instrument would not only further reduce the manual effort involved in analysis of samples, but would also provide a continuous type of monitoring which could be readily interpreted in terms of permissible limits and could be used to correlate isotope formation with variations in plant operation.

Figure 3 (p. 1025) shows the prototype of this monitor.

Even though the identity and distribution of radioisotopes in the water of a river are known and concentrations have been related to accepted limits for drinking water, the overall problem is still not completely defined.

Although the large volume of water in a river may dilute a radioactive waste to extremely low levels, some of the radioisotopes may be picked up by aquatic forms and thus may again become concentrated in certain tissues; this fact has been mentioned by Dr. Lieberman and Dr. Thomas.

The amount to which radiophosphorous and some other isotopes of biological importance are concentrated by Columbia River fish is shown in Table 1, below. This is merely an indication of the kinds of concentrations which may occur in one situation for a few isotopes.

TABLE 1.—*Isotopes concentrated significantly by Columbia River fish*

	Isotope—In decreasing order of abundance in the fish (radioactive half-life)	Concentration factor—If the amount of the isotope in a gram of water is 1, the amount found in a gram of fish (minnows) during the late summer months will be—
P^{32}	14 days	[1] 100,000.
Na^{24}	15 hours	100–1,000.
Zn^{65}	250 days	1,000–10,000.
Cr^{51}	28 days	10.
As^{76}	27 hours	100.
Cu^{64}	13 hours	10.
Sr^{90}	20 years	1,000.

[1] May reach over 1,000,000 for algae.

The basic mechanisms which are responsible for this uptake include absorption directly from the water, metabolism of isotopes consumed with food, and absorption to the exposed surfaces of the organisms. The relative importance of the different mechanisms varies greatly between plants and animals, between different body types, between different environments, between different seasons, and between different isotopes. Even if the concentration of an isotope remains relatively constant in the water, its concentration in the aquatic forms may be in a continuous state of change because of changes in the physical and chemical characteristics of the water and biological changes in the organisms.

All aquatic animals are ultimately dependent upon algae and other plants for the initial concentration of most nutrient elements from the water. Many of the isotopes present in the reactor effluent, including radiophosphorous, are thus concentrated first by algae and then passed on to the fish through food chains. The marked seasonal fluctuations which occur in the radioactive content of fish which live in the Columbia the year round result largely from changes in the fishes' rate of feeding.

Over 90 percent of the activity in fish originates from radiophosphorus which deposits principally in the hard tissues such as the bone and scales. The relative concentration in various fish tissues is shown in figure 5 (p. 1031) and it may be noted that the flesh, which is used for food, is among the least contaminated parts. Several of the variables which affect the concentration of radiophosphorus in fish have been studied under laboratory conditions at Hanford. Such research work is continuing with other isotopes with the expectation that the fundamental principles will become better understood and that observed results can be extrapolated to other waste disposal situations.

In addition to the precautions which are taken to insure that the quantities of waste released to the Columbia River are below appropriate limits for use by the general public, we must also be aware of our responsibilities to take appropriate measures to avoid jeopardizing the valuable commercial and game fish and crops irrigated with river water. These aspects have also been carefully investigated by Hanford biologists.

The population of invertebrate animals which inhabit the river bottom in an area washed by higher than average concentrations of the

effluent remains quite comparable with populations upriver from the reactors and apparently has not been affected in any way. The number of chinook salmon which utilize the Hanford section of the river as a spawning site fluctuates widely from year to year, as do the runs to other parts of the river, but no effect attributable to reactor operation has been discerned. The populations of waterfowl which nest within the reservation seem actually to have benefited from the refugelike protection now afforded them.

More sensitive tests of the toxicity of the effluent to selected forms have been carried out under controlled laboratory conditions over the past 13 years. This work has comprised about 40 separate experiments, many of which have lasted for more than 1 year, and has utilized nearly 700,000 fish of a half-dozen different species. Such tests have clearly demonstrated that the concentration of effluent in the Columbia River is well below the toxic level. Studies on the separate effects of heat and process chemicals have shown that the limiting factor in the toxicity of the effluent is not the radioelements but dichromate which is added to inhibit corrosion in the reactor. From this work has come a recommended limit for the addition of dichromate to the Columbia River, a limit appreciably below that permitted in drinking water for humans and one which is perhaps over 100 times more stringent than would have been arrived at by traditional short exposure methods.

While the concentration of radioisotopes in the effluent is not now the limiting factor in its toxicity, a knowledge of the quantities of particular isotopes which could become deposited in fish without damage is highly desired and would materially assist in developing criteria for the disposal of low level liquid wastes in many situations. Research of this type is in progress at Hanford and data is now available on radiophosphorous.

It appears that if the concentration of this isotope in the flesh of the fish is low enough to permit its use as human food, the radiation received by the fish will not be sufficient to cause damage. Figure 8 (p. 1038) shows the method of administering radioactive material to trout in troughs in our laboratory.

There appears to be essentially no problem associated with the use of reactor effluent water for irrigation. Crops of barley have been grown on experimental plots at Hanford and irrigated with the undiluted effluent. The same plots have been used over and over for the past 7 years, the seed from the previous crop being used in the subsequent year. No significant effects have been observed in these tests nor in supplementary tests where the plants were grown in soil which contained the equivalent of 25 years' accumulation of effluent constituents.

The biological parameters which are required for the establishment of maximum permissible concentrations of radioactive materials in drinking water are being methodically reinvestigated by Hanford biologists. In this field and in many related studies which pertain to the detailed evaluation of a permissible limit, we have determined that the published value appears to require substantial modification. Most often our results have shown the need for a lower value and have resulted in the voluntary acceptance of limits which are much more stringent than the "official" ones.

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In those cases where our data would seem to justify relaxation of the limit, we continue to accept the "official" value until such time as our local evidence influences the appropriate change at the national level.

All of the research and development problems associated with the disposal of reactor effluent to the Columbia River are not concerned with direct efforts. Several studies are now in progress and others are scheduled which, it is hoped, will indicate a means of limiting the production of the most significant isotopes which appear in the effluent. New instruments are also under development to facilitate the early detection of ruptured fuel elements, and thus minimize the release of fission products.

Although the research and development work associated with the disposal of radioactive waste to surface waterways involves a large variety of subjects and embraces many scientific disciplines, the complexity of the problems should not preclude the use of surface waterways for the prudent disposal of radioactive wastes. Through the use of a well-rounded research and development program, it is possible to investigate the several facets of the problem and to provide the information necessary to assure that permissible limits are not exceeded.

Information which is developed for immediate application to one waste disposal situation can be used elsewhere and we may look forward to a time when our knowledge is sufficiently complete to allow accurate prediction of the effects of radioactive waste for a variety of river situations.

Dr. FOSTER. Mr. Chairman, as a supplement to these remarks, I have prepared a paper on the same subject. This has been submitted to the staff of the committee for such disposition as they may feel appropriate.

Representative HOLIFIELD. Thank you very much, Doctor. We will insert it at the end of your statement.

Are there any questions of Dr. Foster?

Representative WESTLAND. First of all, I wish to compliment Dr. Foster on his dissertation on this subject in pretty much words of one syllable which a layman like myself can understand.

I realize that sometimes in these discussions technical terms must be used which are perhaps a little over my head if not the heads of the others.

I would like to ask the Doctor, has the Department of Health of the State of Washington agreed with you on your solution to these problems and the results which you have achieved?

Dr. FOSTER. Quite early in the experience at Hanford there was brought into the picture a special group which is known as the Columbia River Advisory Group. This organization is composed of the executive officers of the Health Department of the State of Washington, the director of the Pollution Commission of the State of Washington, in addition to similar officials of the State of Oregon and the chairman of that particular board is a member of the U.S. Public Health Service.

As a result, our research efforts and exposure measurements in the river have been made available to this body which meets two to three times each year. We keep them informed up to date on the

problems and thoroughly advised and we have their indication that they certainly concur with what evidence we have.

Representative WESTLAND. Of course, the pollution of streams in the State of Washington is of great importance and is constantly being reviewed, I know, by our pulpmill and now from the Hanford project.

Certainly, you are to be complimented in the way the matter has been handled. I would like to ask one further question, Doctor. In periods of low flow in the Columbia do you have to restrain your disposal of this effluent?

Dr. FOSTER. The answer to this is "No." It turns out that the seasonal fluctuations in the Columbia River are certainly advantageous as far as the accumulation of radioactive materials by fish and other organisms are concerned.

We do observe a rather large cyclic variation in the amount of radioactive materials in the fish. It turns out that the time of the year when this is greatest is during the late summer months and early fall, at a time just following the peak flow of the Columbia River.

The cyclic nature of this is due principally to the intake of radioactive materials in the way of food by the fish. This is the period of the year when the fish are feeding most actively.

Low flow in the Columbia River occurs during the cold winter months. At this particular time of the year the amount of radioactive materials observed in the fish is also lowest.

Representative WESTLAND. I have no further questions.

Representative HOLIFIELD. Mr. Bates?

Representative BATES. Doctor, have you made a test of the riverbed itself, to see what sort of accumulation might be building up on the riverbed?

Dr. FOSTER. Yes. This is a a part of a continuing and routine monitoring operation which is carried out not only throughout the Hanford project itself, but also downstream in the fore bay of McNary Dam and occasionally further down the river.

Representative BATES. Have you observed any buildup since you started this test?

Dr. FOSTER. We have not observed any buildup of very long-lived isotopes. I might add on this particular subject that the removal of certain isotopes from the water by the aquatic organisms themselves, results in a very slight accumulation of some of the isotopes (of what we might say of intermediate half life) in these biological and other sedimentary materials settling to the bottom of the river.

About the only buildup I might mention in this regard is that one would expect that since these materials are being removed from the water, we might expect to find them in a little higher concentration elsewhere, and it is these isotopes that are disappearing from the water which can be accounted for in the sediments. This is not, however, a long-range buildup.

Representative BATES. Do you find that the findings of the tests are rather constant?

Dr. FOSTER. Yes. These values will, of course, vary from one time of the year to another, but from 1 year to the next in comparable

seasons, the results are quite comparable and to a degree can be related to increases in plant operation.

Representative BATES. So that subject to the change of seasons there is a constant correlation between the amount that is put in and the actual results of the test?

Dr. FOSTER. That is correct.

Representative HOLIFIELD. Mr. Toll?

Mr. TOLL. Dr. Foster, you state at the bottom of page 4 of your statement that the tests demonstrated that the concentration is well below the toxic level.

Do you have any data that indicate the increase in radioactivity above what the fish would naturally have, natural radiation or background radiation, how close you are getting up to the permissible toxic level?

Dr. FOSTER. In answer to this question I would like to bring out that the limiting factor on the toxicity of the waste, as we see it in the Columbia River, at the present time, to the fish is not the radioactive materials that are present but the dichromate, a common industrial chemical. In terms of the amount of material which could be added to the Columbia River in addition to what is there, we could nearly double the amount of dichromate which is going to the Columbia River before toxic conditions would result.

In terms of the amount of radioactivity which could be added, specifically, radiophosphorous, this is a somewhat different problem. The amounts are also in a different order of magnitude. We know they could be 10 times greater than they are now, and possibly 50 times greater.

Representative HOLIFIELD. Without damage to the fish?

Dr. FOSTER. Without damage to the fish. I think it is rather pertinent that we point out that, although we do have a new and unique kind of waste, we still have with us in conjunction with these problems some of the same industrial type of effluents which have been with us for many, many years and these by themselves, as in our case, may actually be more limiting than the radioactive materials.

Chairman DURHAM. Doctor, since the early days of Hanford, when you first had this problem in building the tanks, can you give us an estimate or do you know the figures on a per gallon basis of the storage we have at Hanford at the present time?

Dr. FOSTER. I am not personally familiar with the figures which go into the storage tanks. As I recall, from other testimony which I believe was included in materials submitted by Dr. Parker, I think the figure there is 52 million gallons.

Representative HOLIFIELD. That was the figure.

Chairman DURHAM. You are still using the storage tank method today, are you not?

Dr. FOSTER. In the separation process, under the waste management, yes, these tanks are definitely being used. I would like to point out, however, that the waste that we are concerned with in the Columbia River is not the fission product type of waste which is being stored in tanks but that which originates from the cooling water.

Chairman DURHAM. You adopted that method, of course, in the beginning.

Dr. FOSTER. That is correct.

Chairman DURHAM. You have been in operation now how many years?

Dr. FOSTER. Since the first reactors were started up late in 1944.

Chairman DURHAM. Your testimony pertains to the low-level wastes which are released into the river and not to the high-level waste which is put into the tank?

Dr. FOSTER. That is correct.

Representative BATES. Regarding that experiment of feeding fish, is the degree of radioactivity contained in that food about the same degree as the effluent that comes out of the pipe?

Dr. FOSTER. In setting up this particular experiment we attempted to stimulate or duplicate the amount of radioactive material which would be consumed by a fish in the Columbia River feeding naturally upon the fish food organisms which had accumulated radioactive material from the water.

In other words, we attempted to duplicate as nearly as we could the total deposition of radioactive materials in the fish. We found that this level caused no damage. We found that a level 10 times higher than that did not cause damage.

It was necessary to go to even higher levels before we were able to produce damage.

Representative BATES. The amount of radioactivity in the algae or whatever they are eating is of greater concentration than the amount that is coming into the river originally?

Dr. FOSTER. That is right.

Representative HOLIFIELD. Thank you, Dr. Foster.

We also have several papers on "The Disposal of Low-Level Liquid Wastes to Surface Waters" for the record at this point.

(Dr. Foster's formal statement and additional papers follow:)

RESEARCH AND DEVELOPMENT PROGRAMS RELATED TO THE DISPOSAL OF REACTOR EFFLUENT TO THE COLUMBIA RIVER

By

Richard F. Foster of the Hanford Laboratories,
Hanford Atomic Products Operation,
General Electric Company.

Introduction

Waste disposal to surface waterways has several features in common with disposal to other types of environments. We are faced with such problems as how effectively the waste is diluted as it is transported to other locations, where and in what form the waste may again affect man's welfare, activities, or interests, what concentrations of the waste can be considered safe under the circumstances, what sorts of measurements and controls are necessary to assure that safe limits are not exceeded, and what practical action can be taken to minimize the quantity of the waste or the problems associated with it.

When solutions to these general problems are sought for surface waterways, we find that in some cases the answers are more easily obtained than for other environments. In other cases the answers are more elusive. Liquid waste discharged into a river with a known flow rate is almost certain to be carried downstream at rates which can be measured with reasonable accuracy. This allows a precision in the prediction or measurement of its concentration and time and place of arrival which is not common to ocean, atmospheric, or ground disposal. On the other hand, it is difficult to apply mathematical expressions which describe the diffusion of liquid waste in tortuous rivers with an ever changing stream bed cross section. Surface waterways are also subject to wide fluctuation in their physical, chemical and biological characteristics and each of these is closely related to the magnitude of the problem which may be associated with the disposal of radioactive waste. A

single set of measurements is not sufficient, therefore, and several sets may be necessary to describe conditions under different circumstances.

While field measurements are as necessary for defining the course of waste released to surface waterways as they are for wastes released to other environments, such measurements will usually be less expensive in time and dollars in the case of the surface waterways. This comparative ease of measurement does not imply that this is always the preferred means of disposal. Indeed, an inverse relation is apt to be the case since accessibility enhances exposure for the general public, and for biological forms.

Research and development work at Hanford has produced a sufficient amount of information on the expected time, place, and concentration of reactor effluent isotopes in Columbia River water and in plants and animals to provide assurance that effluent disposal practices are reasonable and justified. These studies have been accompanied by investigation of related problems which include determination of the nature and degree of exposure associated with each water use, development of precision methods for quickly identifying and measuring the concentrations of significant radioisotopes, inquiry into the sources and production of radioisotopes which appear in the effluent, and evaluation of the efficacy of existing or proposed effluent handling methods. Biological studies have also provided information on the mechanisms by which various plants and animals pick up the radioactive materials, where the isotopes are deposited, and metabolic characteristics bearing on the validity of the recommended maximum permissible concentrations.

Many of these studies are so closely associated with plant operation that they could be considered equally as well under waste management. Indeed, a close liaison exists between the manufacturing components and the research teams which allows immediate application of new information on the one hand and rapid investigation of new problems on the other.

The Distribution of Reactor Effluent in The Columbia River

Since the Columbia is the second largest river in the United States and has a normal flow rate of about 80,000 cubic feet per second in the vicinity of the reactors, an abundance of water is available for dilution of the reactor effluent. By itself, however, this fact is not sufficient to define the exposure to water users downstream or to the aquatic organisms. It must be supplemented with observations on how completely and how quickly the effluent becomes mixed with the river water, how much of the radioactive material is retained by the river sediments, and how much is accumulated by fish and other aquatic organisms. Neglect of these factors could result in ultra-conservative limits in some cases and yet ignorance of other sources of exposure.

Several surveys have been made to map the distribution of the effluent in the Columbia River (1), (2), (3), and to determine the length of time required for the effluent to travel to points of water use under various hydrographical and operational conditions (4). The methods used to obtain the required information include sounding to determine bottom contours, meter readings and float studies to determine the speed of the current, temperature readings and visible dye application for definition of the effluent plume, and counting of radioactivity to determine the distribution pattern. A new scintillation-type instrument (5) is under development which should materially assist in future mapping of the effluent dispersion pattern. Figures 1 and 2 are included here to illustrate the type of information which is obtained.

Identification and Measurement of Radioactive Materials

While the gross radioactivity of the reactor effluent at various points of interest can be measured by comparatively simple counting techniques, such

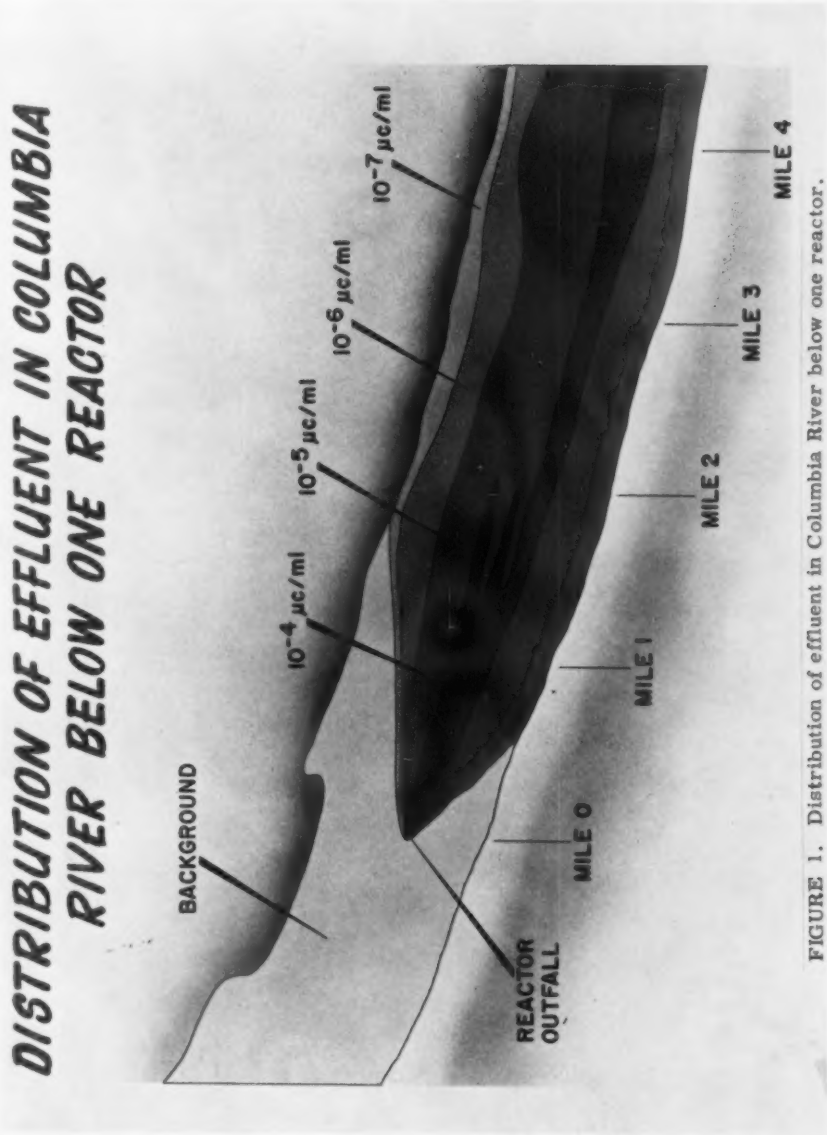

FIGURE 1. Distribution of effluent in Columbia River below one reactor.

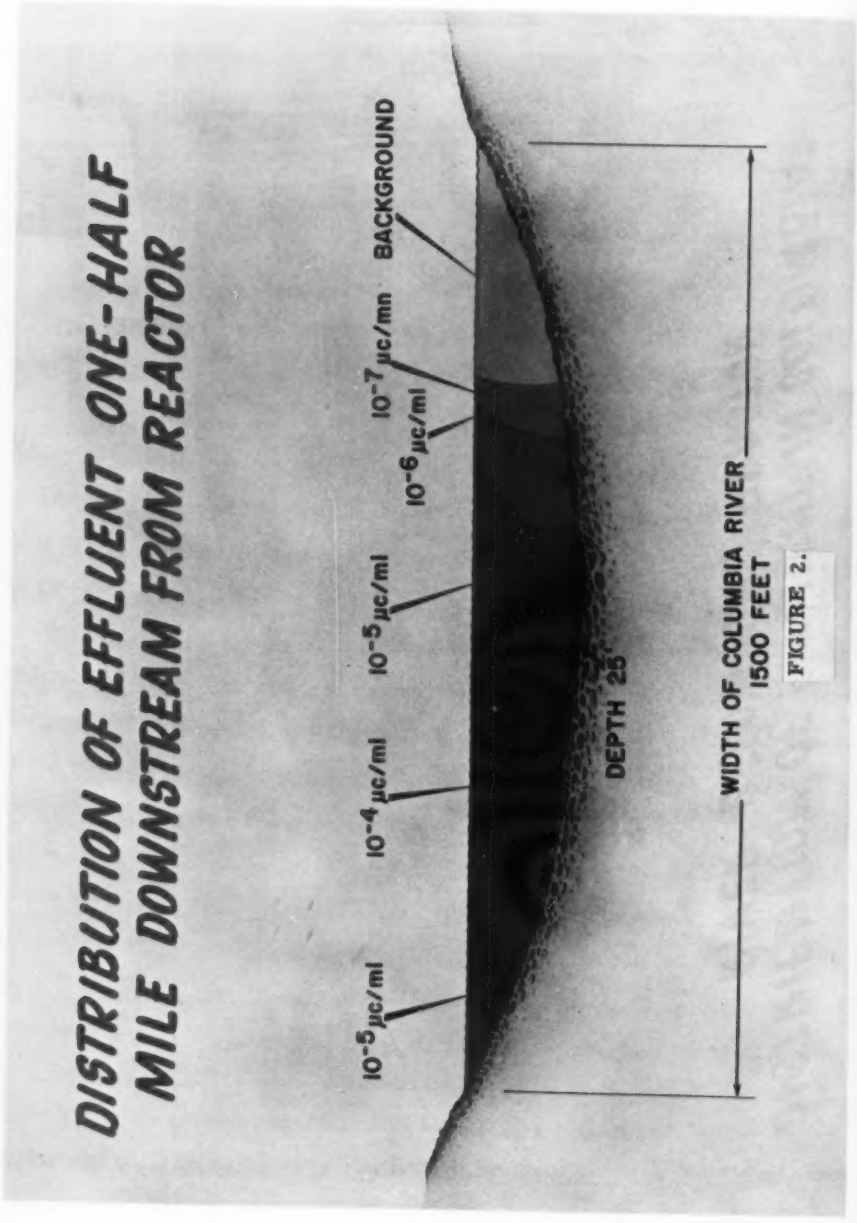
DISTRIBUTION OF EFFLUENT ONE-HALF MILE DOWNSTREAM FROM REACTOR
10^{-5} µc/ml
10^{-4} µc/ml
10^{-5} µc/ml
10^{-6} µc/ml
10^{-7} µc/ml
BACKGROUND
DEPTH 25'
WIDTH OF COLUMBIA RIVER
1500 FEET

FIGURE 2.

measurements are not sufficient to define the radiological problems with the required accuracy. The reactor effluent probably contains as many as 200 different radioisotopes, with some 170 possible from fission alone. The contribution which each of these isotopes makes to the over-all exposure changes according to how the water is used, such as for drinking, swimming, boating, industry, irrigation, or production of fish and wildlife (6), (7), (8). The contribution also varies according to the types of exposure involved, such as dose to the gastro-intestinal tract, to the reproductive organs, or to some other "critical" organ such as bone (9). Further, the most abundant radioisotopes are not necessarily the ones which present the greatest radiation problems. An example is radiophosphorus which makes up less than 0.5 per cent of the activity of the effluent but which contributes virtually all of the radiation exposure associated with the use of fish as food (10).

The need to identify and measure the individual isotopes present in reactor effluent water in order to evaluate their hazard under the different circumstances has resulted in the development of analytical methods which are capable of measuring extremely small quantities of the isotopes (11). From a knowledge of the abundance of each isotope it has been possible to compute its significance to the total exposure (12). It would be impractical, however, to attempt to analyze for the full complement of isotopes on a routine basis. For this reason only those isotopes or groups of isotopes which make a significant contribution to the exposure are measured as a part of the routine effluent monitoring program (8).

Until 1957 the significant isotopes were measured by radiochemical procedures which required that the radioisotopes be chemically separated from all but traces of other radioisotopes and even from non-radioactive materials in order that the beta radiation could be counted. Since most

of the isotopes which emit beta particles also emit gamma rays which are much more penetrating and which have energies that are characteristic of particular isotopes, instrumental methods of analysis were developed (13). Adaption of the gamma-ray spectrometer and other instrumentation to the routine analysis of reactor effluent water has resulted in substantial savings in the manpower and length of time required to process the samples. It has also resulted in improved sensitivity which has made it more convenisnt to evaluate exposure at the points of water use, such as municipal water supplies. Other advantages of rapid instrumental analysis include applicability to a variety of specimen material and even live animals, and the ability to measure the depletion of specific radioisotopes from the Columbia River by natural processes (14).

Developmental work in instrumental analysis is still being carried forward. One objective is to perfect an automatic waste stream analyzing monitor which could detect, measure, and record the concentrations of individual isotopes of special interest. Such an instrument would not only further reduce the manual effort involved in analysis of effluent samples but would also provide a continuous type of monitoring which could be readily interpreted in terms of permissible limits and could be used to correlate isotope formation with variations in plant operation. Figure 3 shows the prototype of this monitor which uses a combination of mechanical, chemical, and electronic operations to determine automatically the concentration of Na^{24}, Mn^{56}, Cu^{64}, As^{76}, Np^{239}, P^{32}, and Si^{31} and the total beta particle emission rate in the effluent stream from a reactor.

Accumulation of Radioactive Materials By Columbia River Organisms

Even though the identity and distribution of radioisotopes in the water of a river are known and concentrations have been related to accepted limits

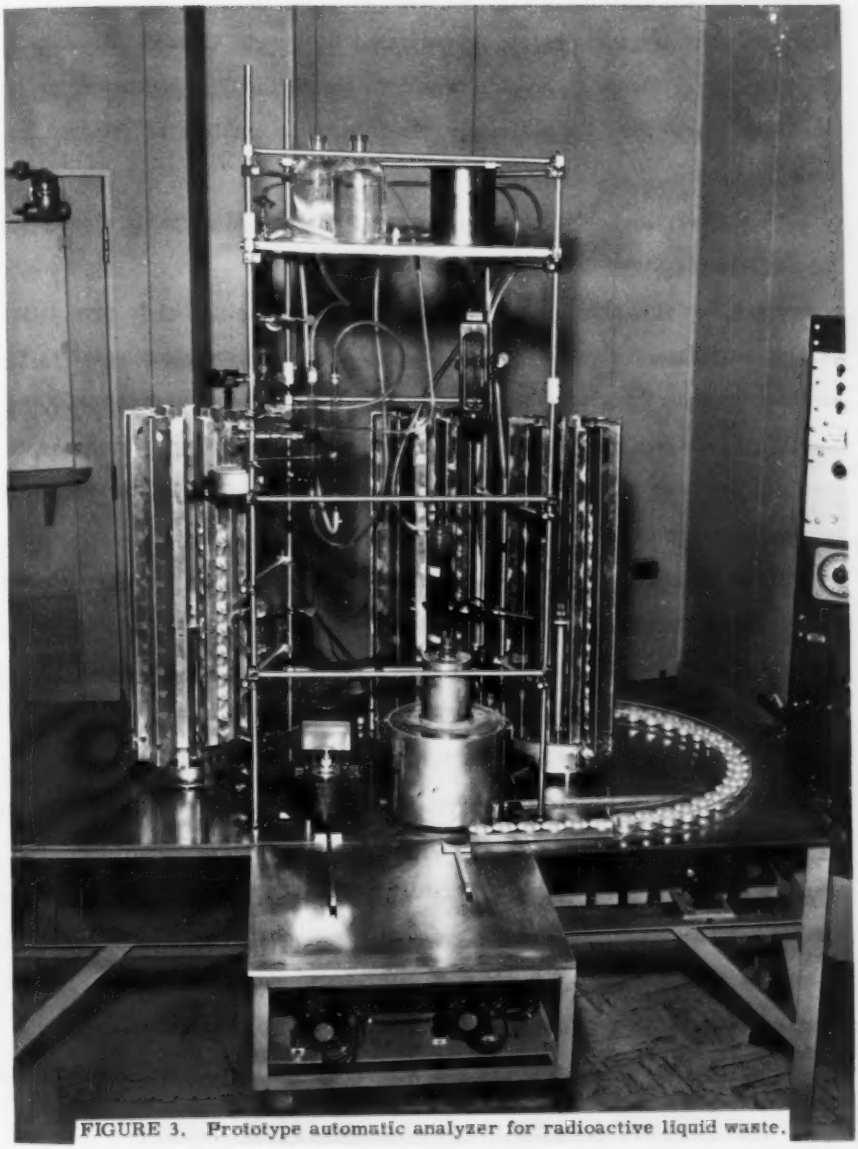

FIGURE 3. Prototype automatic analyzer for radioactive liquid waste.

for drinking water, the over-all problem is still not completely defined. Although the large volume of water in a river may dilute a radioactive waste to extremely low levels, some of the radioisotopes may be picked up by aquatic forms and thus may again become concentrated in certain tissues. Thus, neither the radiation exposure to aquatic organisms nor to people who use them as foods can be evaluated from the maximum permissible concentrations established for drinking water.

Soon after the Hanford reactors were put in operation, exploratory sampling of Columbia River fish showed that they concentrated radiophosphorus and some other isotopes from the water (15). This observation led to more comprehensive sampling of river organisms (16), (17) and to laboratory research designed to show the extent of the concentration and the mechanisms involved (18), (19). It was soon apparent that the radioisotopes which were most strongly deposited were the radioactive forms of chemical elements which were common constituents of the organisms (20), (21).

Since the substance of which the fish and other aquatic life is made must at one time have existed as nutrient material dissolved in the water, the processes by which the organisms are able to grow, or even to maintain themselves, are essentially the same as those involved in the concentration of the radioisotopes. Phosphorus can be used as an example. The amount of phosphorus dissolved in Columbia River water is very low - only about one gram in each 100,000,000 grams of water. On the other hand there is about one gram of phosphorus in each 180 grams of fish. In essence, this means that if a fish grew in size by one gram, it would need to have removed the phosphorus from about 500,000 grams of water (neglecting other sources) in order to satisfy its requirement for this element. In this case we can assume that radioactive phosphorus (P^{32}) behaves in the same way as the

natural phosphorus in the river water and that a "concentration factor" of 500,000 is theoretically possible. The observed concentration in Columbia River fish amounts to about 100,000 during the late summer and thus falls considerably short of the theoretical value. The observed value is less because the biological processes required to deposit and exchange the phosphorus in the body of the fish are long in comparison to the radioactive half-life of the P^{32}, which is about 14 days. Isotopes of other elements are also concentrated by aquatic organisms. While the degree of concentration is generally not as great as for phosphorus, it is of sufficient magnitude in many cases to warrant attention. The concentration factors which have been observed for some of the most significant isotopes are listed in Table 1 for a few representative types of Columbia River organisms.

The basic mechanisms which are responsible for the uptake of radioactive materials by aquatic forms include absorption directly from the water into the protoplasm of the organisms, metabolism of isotopes consumed with food, and adsorption to the exposed surfaces of the organisms. The relative importance of the different mechanisms varies greatly between plants and animals, between different body shapes and sizes and compositions, between different environments, between different seasons and between different isotopes. The relative concentration of reactor effluent isotopes in several different types of Columbia River organisms during the fall of the year is shown in Figure 4. Even if the concentration of an isotope remains relatively constant in the water, its concentration in the aquatic forms will be in a continuous state of change because of changes in the physical and chemical characteristics of the water and biological changes in the organisms.

While fish can utilize limited quantities of some elements such as sodium directly from the water, they depend almost entirely upon their food

Table 1

Observed Concentration Factors ($\frac{\text{uc/g of organism}}{\text{uc/ml of water}}$)
For Significant Isotopes Found in Columbia River Organisms

Isotope	Algae(a)	Insect(b) Larvae	Fish(c)
P^{32}	100,000-1,000,000	100,000	100,000
Zn^{65}	100,000	10,000	1,000-10,000
Cs^{137}(d)	1,000-5,000	1,000	5,000-10,000
Sr^{90}	10,000	100	1,000
Na^{24}	100	100	100-1,000
As^{76}	10,000	1,000	100
Sc^{46}	100,000	1,000	10
Cr^{51}	100-1,000	100-1,000	10
Cu^{64}	10,000	1,000	10

Many of these values are not yet well defined and are subject to revision.

(a) *Stigeoclonium sp.*

(b) *Hydropsyche sp.*

(c) *Richardsonius sp.*

(d) Data for Cs^{137} obtained from a pond environment rather than the Columbia River and species are different from those listed above.

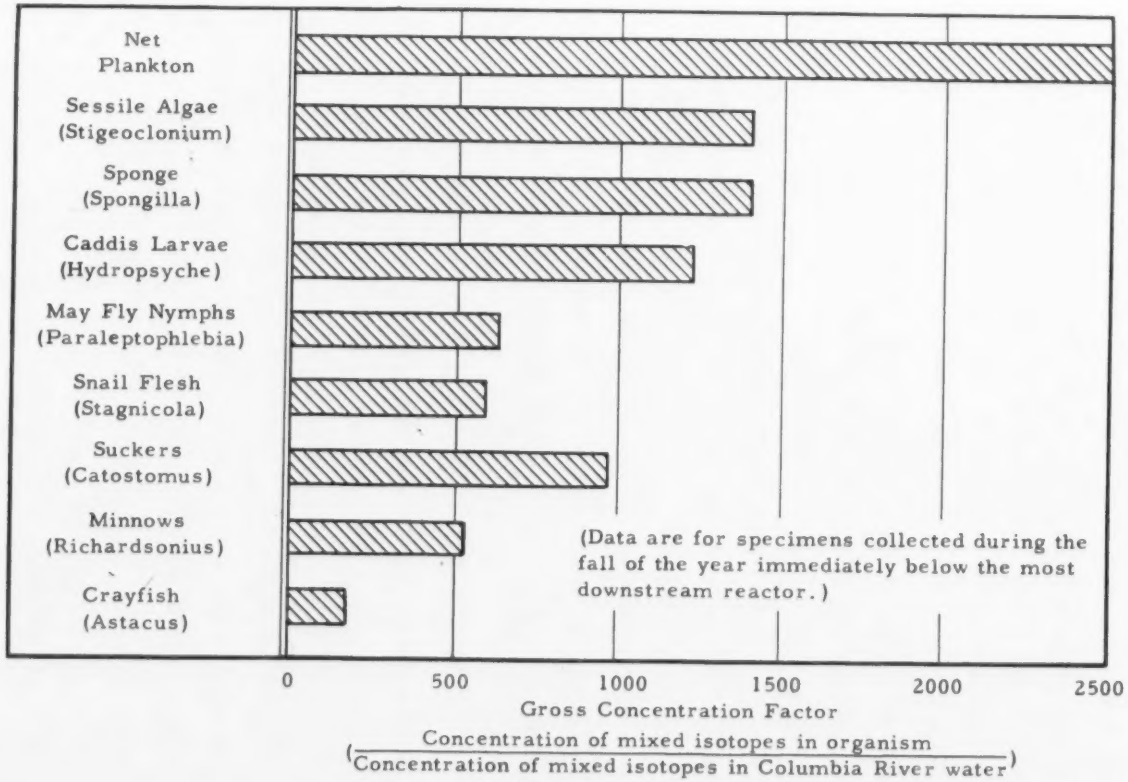

FIGURE 4

RELATIVE CONCENTRATION OF RADIOISOTOPES IN COLUMBIA RIVER ORGANISMS

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as the source of nutrients. All aquatic animals are ultimately dependent upon algae and other green plants for the initial concentration of most nutrient elements from the water. Many of the isotopes present in the reactor effluent water, including radiophosphorus, are thus concentrated first by algae and then passed on to the fish through food chains. The amount of radioactive material found in Columbia River fish is, therefore, largely dependent upon the feeding habits of the fish. The species of fish, such as the suckers, which feed directly upon the algae that grows on the rocks of the river bottom, become more contaminated than species such as the bass which obtain the isotopes third or fourth hand via other food organisms (16). The adult salmon, which do not feed after leaving the ocean on their spawning migration, remain virtually uncontaminated.

The marked fluctuations which occur in the radioactive content of Columbia River fish between summer and winter result largely from changes in the fishes' rate of feeding. This is in turn related to metabolic rate which is controlled by temperature. When the intake of P^{32} diminishes during the winter months, the accumulated burden deposited in the fish declines through radioactive decay. Only a slight decline results for radiozinc, however, since this isotope has a half-life of 245 days. Radioisotopes which have been found in Columbia River fish include, in diminishing order of abundance, P^{32}, Na^{24}, Zn^{65}, Cr^{51}, Mn^{56}, As^{76}, Cu^{64}, Sr^{90}, Sc^{46}, and Cs^{137} (22). Over 90 per cent of the activity originates from the P^{32} which deposits principally in the hard tissues such as the bone and scales, but is also abundant in some visceral organs. The relative concentration in various fish tissues is shown in Figure 5. It should be noted that the flesh, which is used for food, is among the least contaminated parts.

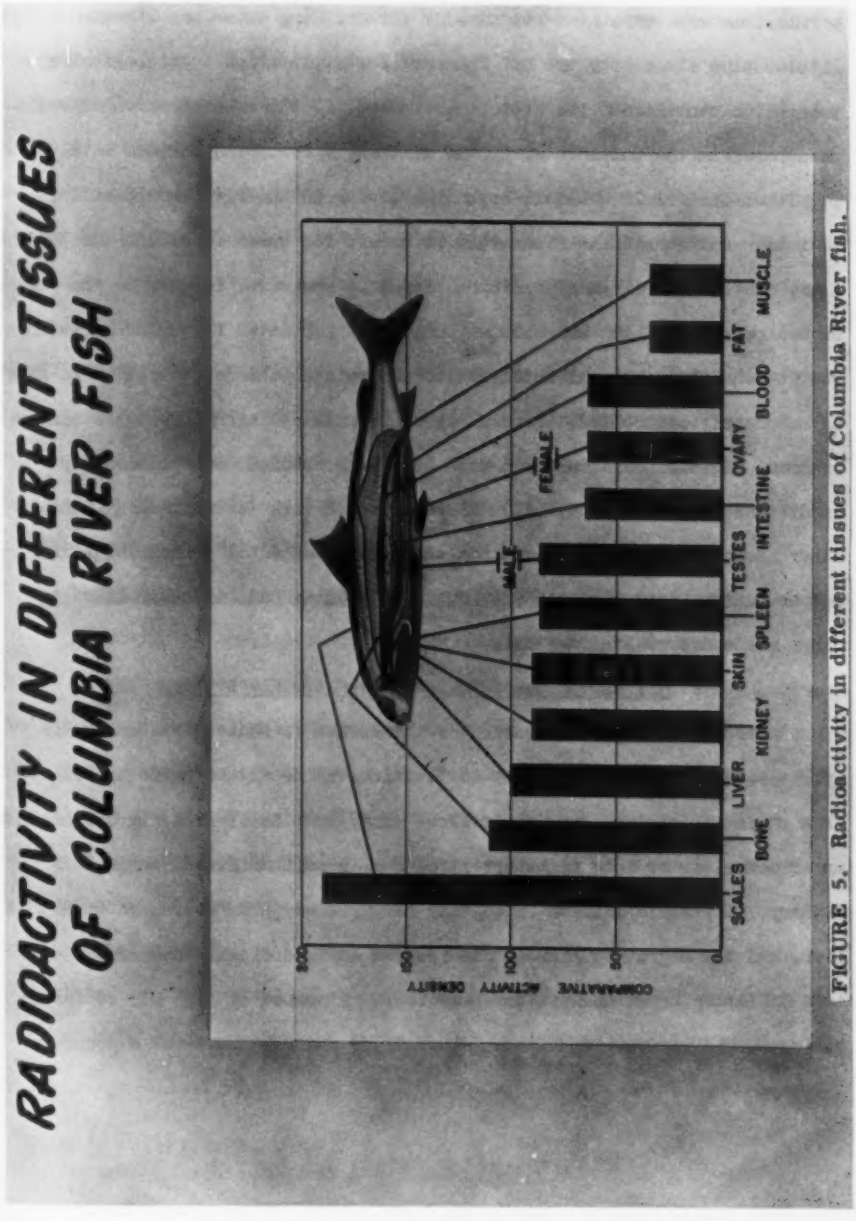

FIGURE 5. Radioactivity in different tissues of Columbia River fish.

Since the biological importance of each element is different, the relative concentrations of various isotopes in the water are of little significance in the estimation of the exposure to the various organisms. The maximum permissible concentrations recommended for drinking water are likewise of little value since they are not intended for application to biological systems which concentrate the isotopes. Indeed, if the concentration of radiophosphorus in the Columbia River was allowed to reach the maximum level permitted for drinking water, organisms living in the river would suffer radiation damage and the fish would be unsafe for human food. At the present time, the concentration of radiophosphorus in the river is only on the order of one per cent of the non-occupational limit permitted for drinking water; yet it requires continual attention to assure that the concentration in fish is adequately controlled. Several of the variables which affect the concentration of radiophosphorus in a fish have been studied under laboratory conditions at Hanford (23) (24). Such research work is continuing with other isotopes with the expectation that the fundamental principles will become better understood and that observed results can be extrapolated to other waste disposal situations.

Translocation of Radioactive Materials by Fish

Another potential consequence of the uptake of radioactive materials by river fish is their transport to locations which may be quite different from those anticipated from river flow. Many species of fish migrate either up or downriver or into tributary streams at some time during their life history. Any radioisotopes which they have picked up of course go with them, and the migrating fish do not respect any artificial boundaries.

While the total quantities of isotopes relocated by fish may be insignificant, the radioactive fish may themselves contribute to the exposure of

fishermen who catch and eat them. The whitefish of the Columbia River are, perhaps, an outstanding example. The whitefish which inhabit the section of the river downstream from the reactors accumulate some of the radioisotopes from the reactor effluent. During the spring, and to a greater extent during the late fall, many of these fish migrate upriver where they are caught by fishermen above the project boundary (10). Figure 6A shows the per cent of adult whitefish collected about 15 miles upriver from the nearest reactor which contained effluent isotopes. Since the concentration of radiophosphorus in some individual fish collected at this site was as great as that found in fish below the reactors, the journey must have taken only a few days' time, otherwise appreciable radioactive decay would have reduced the level. The significance of this migration to the average concentration of radioisotopes in fish collected above the project boundary is illustrated in Figure 6B. The average contribution which whitefish caught from this area would contribute an exposure of less than five per cent of the maximum permissible limit to people who eat them, however.

The Direct Effects upon Aquatic Organisms and Irrigated Crops

In addition to the precautions which are taken to insure that the quantities of waste released to the Columbia River are below permissible limits for use by the general public, we must be aware of our responsibilities to take appropriate measures to avoid jeopardizing the valuable commercial and game fish and crops irrigated with river water. These aspects have also been carefully investigated by Hanford biologists.

One method of measuring the possible effect of the effluent on the river organisms is to periodically make census of certain groups. Figure 7 shows biologists making a census of selected organisms. The population of invertebrate animals which inhabit the river bottom in an area washed by higher-

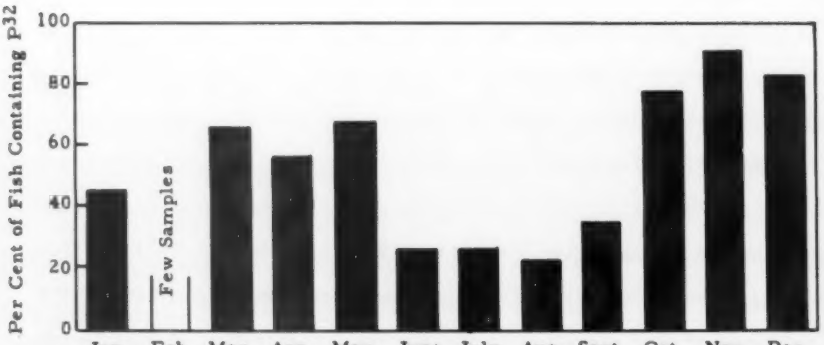

FIGURE 6-A PER CENT OF COLUMBIA RIVER WHITEFISH COLLECTED ABOUT 15 MILES ABOVE REACTORS WHICH CONTAINED P^{32}

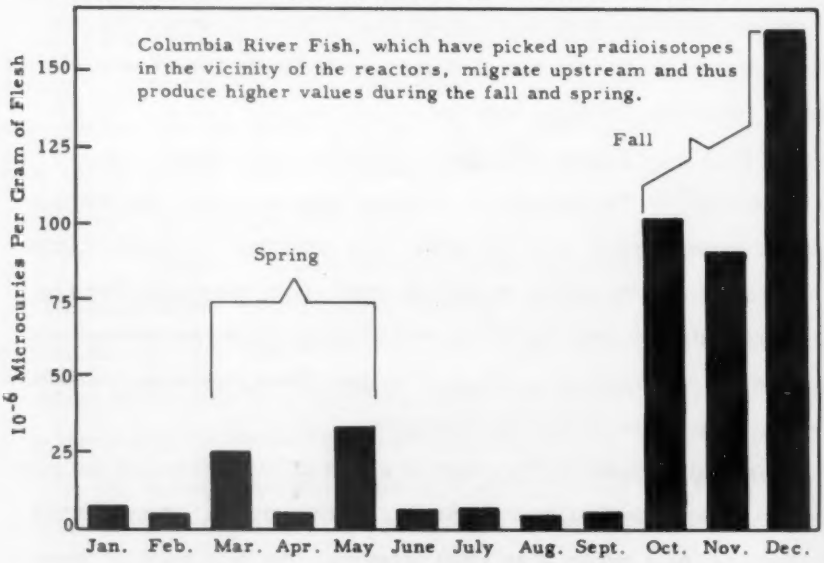
Columbia River Fish, which have picked up radioisotopes in the vicinity of the reactors, migrate upstream and thus produce higher values during the fall and spring.
Fall
Spring
10^{-6} Microcuries Per Gram of Flesh
150
125
100
75
50
25
0
Jan. Feb. Mar. Apr. May June July Aug. Sept. Oct. Nov. Dec.

FIGURE 6-B
SEASONAL CHANGES IN THE CONCENTRATION OF RADIOISOTOPES IN WHITEFISH COLLECTED ABOUT 15 MILES ABOVE THE HANFORD REACTORS

FIGURE 7. Equipment used to determine the abundance of bottom organisms in the Columbia River.

than-average concentrations of the effluent remains quite comparable with populations upriver from the reactors and apparently has not been affected in any way (25). The numbers of chinook salmon which utilize the Hanford section of the river as a spawning site fluctuates widely from year to year, due to a variety of natural causes and to the varying success of the several fisheries (26). It has not been possible to discern any effects on the populations of salmon attributable to the operation of the Hanford reactors. The populations of waterfowl which nest within the reservation seem actually to have benefited from the refuge-like protection afforded them (27).

More sensitive tests of the toxicity of the effluent and its component parts to selected forms have been carried out under controlled laboratory conditions over the past 14 years. This work has comprised about 40 separate experiments, many of which have lasted for more than one year, and has utilized nearly 700,000 fish of a half-dozen different species including the salmon, trout, and whitefish which are of greatest value to the area. Such tests have consistently shown that the quantity of effluent released to the river is less than that which would cause any indication of toxicity (28). Studies on the separate effects of heat and process chemicals have shown that the limiting factor in the toxicity of the effluent is not the radioelements but dichromate which is added to inhibit corrosion in the reactor (29), (30), (31). From this work has come a recommended limit for the addition of dichromate to the Columbia River (32) - a limit appreciably below that permitted in drinking water for humans and one which is perhaps over one hundred times more stringent than would have been arrived at by traditional short exposure methods.

While the concentration of radioisotopes in the effluent is not now the limiting factor in its toxicity, a knowledge of the quantities of

particular isotopes which could become deposited in fish without damage is highly desired. Such information would materially assist in developing criteria for the disposal of low level liquid wastes in many situations. Research of this type has been carried out at Hanford and pertinent data are now available on radiophosphorus (23). It appears that if the concentration of this isotope in the flesh of the fish is low enough to permit its use as human food, the radiation received by the fish will not be sufficient to cause damage. Figure 8 shows the method of administering radioactive food to trout.

There appears to be essentially no problem associated with the use of reactor effluent water for irrigation. Crops of barley have been grown on experimental plots at Hanford and irrigated with the undiluted effluent (33). These plots are shown in Figure 9. The same plots have been used over and over for the past seven years, the seed from the previous crop being used in the subsequent year. No significant effects ascribable to radiation have been observed in these tests nor in supplementary tests where the plants were grown in soil which contained the equivalent of 25 years' accumulation of undiluted effluent constituents. Mutation rate as well as yield and quality were among the effects studied.

The concentration of effluent isotopes which accumulate in irrigated vegetation is only slightly above the background level and does not contribute significantly to the radiation exposure of people who eat the crops (12).

Related Problems

Not all of the research and development problems associated with the disposal of reactor effluent to the Columbia River are concerned with immediate effects. Some effort must also be devoted to ways and means of

FIGURE 8. Method used to administer radioactive food to fish.

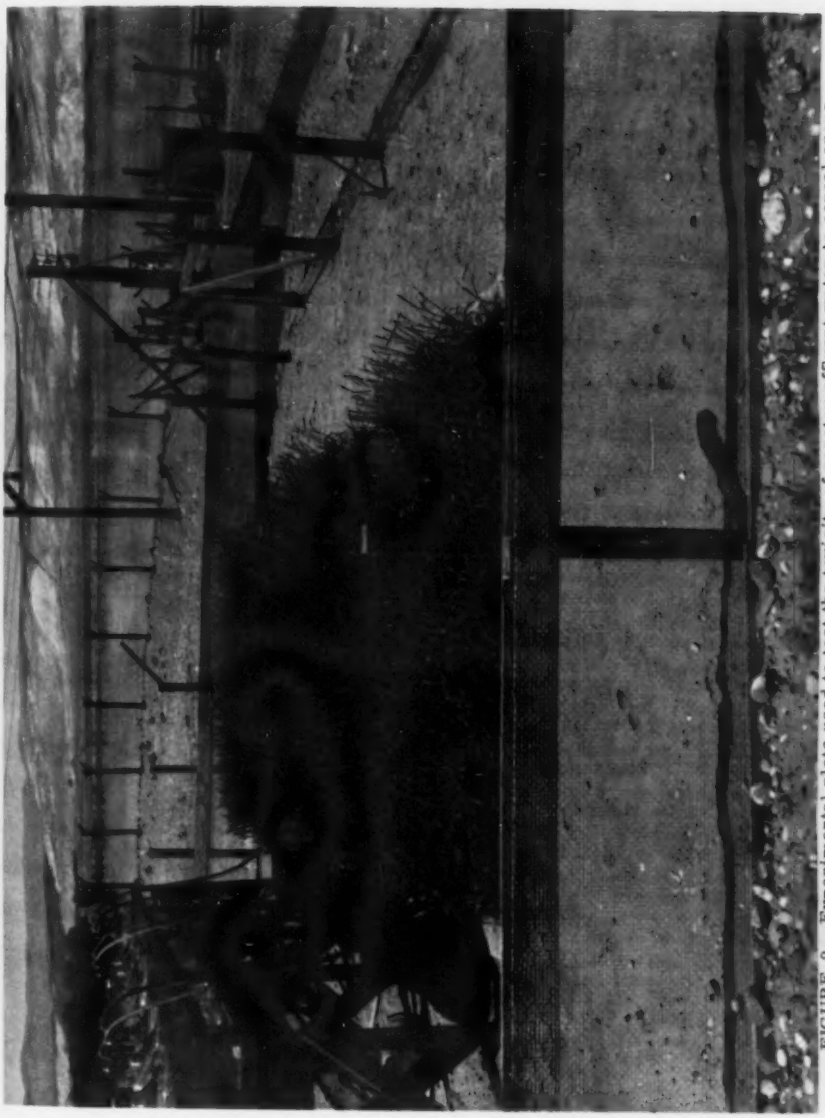

FIGURE 9. Experimental plots used to test the toxicity of reactor effluent water to cereal crops.

limiting the formation of radioactive materials which appear in the effluent, to measuring the need and effectiveness of existing or proposed effluent handling methods, and to testing the validity of recommended maximum permissible limits.

Isotope Formation

Of the many different isotopes which appear in the reactor effluent water, radio-arsenic (As^{76}) is the one which contributes most significantly to the exposure of people in the vicinity of Pasco and Kennewick who drink water from the Columbia and radio-phosphorus (P^{32}) is the one which contributes the greatest part of the exposure to the fish. Several studies are now in progress and others are scheduled which, it is hoped, will indicate a means of limiting the production of these isotopes. Some of the studies seek to establish a correlation between isotope formation and operating variables, others involve actual production tests in which the characteristics of the cooling water are changed in an attempt to effect the desired reduction (34).

Fuel Element Ruptures

When there is a failure in the aluminum cladding of the uranium fuel elements, fission-product isotopes are released into the effluent until the reactor is shut down and the offending element discharged. Although rupture debris enters in the Columbia River only intermittently (6), (35), it may contribute as much as 10 per cent of the exposure received from drinking the water because of the more hazardous isotopes present. Such exposure could be reduced by early detection of ruptures and new instruments are now under development to accomplish this.

Basically two methods of improved detection are being studied: in one case instruments would scan the radiation emanating from the exit piping of each fuel channel; in the other, water samples from both vertical and horizontal collection systems would be analyzed and the offending fuel channel identified from coordinate type data.

Because of the potential effects from thermal shock, the older retention basins cannot now be used effectively to catch rupture debris and divert it from the Columbia River. Consideration is being given to changing the status of these basins from that of retention to the perhaps more valuable function of debris interception. Elimination of the comparatively brief retention time which they now provide would not significantly change the exposure at the nearest downstream municipality using river water for sanitary purposes and biological studies have demonstrated that the fish would not be significantly affected (36).

Only traces of the long-lived fission products which are characteristic of rupture debris have been detected in Columbia River fish. Potentially, however, the uptake of such materials either by humans from the water or by fish could be a limiting factor on the quantity of rupture debris released to the river. A considerable amount of research work remains to be done in this area in order to provide the basic knowledge necessary to establish the proper limits.

Revision of Permissible Limits For Radioactive Materials in Water and Food

In order to estimate the exposure to humans which results from the reactor effluent the concentration of certain isotopes in Columbia River water and fish is routinely compared to standards (maximum permissible concentrations) established by the National Committee on Radiation Protection and Measurements. While such standards are based on the best available information on the behavior of each isotope within the body, we must recognize that additional and refined information is needed in many instances. Biologists at Hanford have been methodically re-investigating the biological parameters required for the establishment of maximum permissible concentrations. This work has included some of the isotopes present in reactor effluent.

To determine whether emphasis was being placed on the proper isotopes of the effluent mixture, rats were fed concentrated effluent for periods up to one year (37). The kinds and amounts of isotopes that were deposited in the rats indicated that the emphasis was only partially correct and that the radiation exposure due to drinking river water was considerably less than that estimated from the concentration of isotopes in the water (38). The amounts of radiophosphorus (P^{32}) and radiozinc (Zn^{65}) that deposited in the bones of rats were different from those predicted from published data on which permissible limits are based. Data subsequently obtained from feeding of these two isotopes suggest that the existing limit for P^{32} may be overly conservative while that for Zn^{65} may not be low enough. Figure 10 shows one method used to administer solutions of radioisotopes to rats.

In this field and in many related studies at Hanford which pertain to the detailed evaluation of a permissible limit, we have determined that the published value appears to require substantial modification. Most often our results have shown the need for a lower value and have resulted in the voluntary acceptance of limits which are much more stringent than the "official" ones. In the special case of radiophosphorus, in which our data would seem to justify relaxation of the limit, we continue to accept the "official" value until such time as our local evidence influences the appropriate change at the national level.

Conclusion

From the paragraphs above it should be apparent that the research and development work associated with the disposal of radioactive waste to surface waterways involves a large variety of subjects and embraces many scientific disciplines. While the collection of hydrographic data is essential, such data alone are insufficient for accurate evaluation of all of the radiological

FIGURE 10. Method used to administer solutions of radioisotopes to rats.

problems. Complete evaluation must also be based on detailed knowledge of the environmental, biological, and operational variables and upon accurate isotopic analysis.

The complexity of the problems should by no means preclude the use of surface waterways for the prudent disposal of radioactive wastes. Through the use of a well rounded research and development program, which functions in close cooperation with the production facilities, it is possible to investigate the several facets of the problem and to provide the information necessary to assure that permissible limits are not exceeded. Information which is developed for immediate application to one waste disposal situation may also be useful elsewhere and we may look forward to a time when our knowledge is sufficiently complete to allow accurate prediction of the effects of radioactive waste for a variety of river situations.

1. Honstead, J. F., J. W. Healy, and H. J. Paas, "Columbia River Survey, Preliminary Report," Document HW-22851 (1951) (SECRET).

2. Honstead, J. F., "Columbia River Survey 1951, 1952, and 1953," Document HW-32506 (1954) (SECRET).

3. Rostenbach, R. E., "Columbia River Survey 1954-1955," Document HW-43529 (1956) (SECRET).

4. Soldat, J. K., "Columbia River Travel Time Measurements by Float Methods," Document HW-41275 (1956) (SECRET).

5. McCall, R. C., "Semi-portable High Sensitivity Scintillation Counter," Document HW-54676 (1957) (UNCLASSIFIED)

6. Healy, J. W. and R. E. Rostenbach, "Influence of Hanford Reactors on Domestic Use of Columbia River Water," Document HW-36862 (1955) (SECRET).

7. Clukey, H. V., "Radiation Aspects for River Navigation Through Hanford Project," Document HW-47152 (1956) (CONFIDENTIAL).

8. Healy, J. W., "Reactor Effluent Monitoring," Document HW-45725 (1956) (CONFIDENTIAL).

9. Clukey, H. V., "Method of Calculating Columbia River Drinking Water Exposure," Document HW-49214 (1957) (CONFIDENTIAL).

10. Watson, D. G. and J. J. Davis, "Concentration of Radioisotopes in Columbia River Whitefish in the Vicinity of the Hanford Atomic Products Operation," Document HW-48523 (1957) (DECLASSIFIED).

11. Matsumoto, W. Y., D. L. Reid, and Z. E. Carey, "Report on the Radiochemical Analysis of Hanford Reactor Effluent Water for the Period January, 1951 to January 1954," Document HW-32141 (1954) (SECRET).

12. Healy, J. W., B. V. Andersen, J. K. Soldat, and H. V. Clukey, "Radiation Exposure to People in the Environs of a Major Atomic Energy Plant," prepared for the 1958 International Conference on the Peaceful Uses of Atomic Energy. Paper No. 743.

13. Perkins, R. W., "A Gamma-Ray Spectrometric System of Analysis for Eleven Reactor Effluent Water Radioisotopes," Document HW-51216 (1958) (CONFIDENTIAL).

14. Nielsen, J. M. and R. W. Perkins, "The Depletion of Radioisotopes from the Columbia River by Natural Processes," Document HW-52908 (1957) (SECRET).

15. Herde, K. E., "Radioactivity in Various Species of Fish from the Columbia and Yakima Rivers," Document HW-35501 (1947) (SECRET).

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References (Contd.)

16. Olson, P. A., Jr., and R. F. Foster, "Accumulation of Radioactivity in Columbia River Fish in the Vicinity of the Hanford Works," Document HW-23093 (1952) (DECLASSIFIED).

17. Davis, J. J., D. G. Watson, and C. C. Palmiter, "Radiobiological Studies of the Columbia River through December, 1955," Document HW-36074 (1956) (SECRET).

18. Olson, P. A., Jr., "Observations on the Transfer of Pile Effluent Radioactivity to Trout," in "Biology Research - Annual Report 1951," Document HW-25021 (1952) (DECLASSIFIED).

19. Whittaker, R. H., "Removal of Radiophosphorus Contaminant from the Water in an Aquarium Community," in "Biology Research - Annual Report 1952," Document HW-28636 (1953) (UNCLASSIFIED).

20. Foster, R. F. and J. J. Davis, "The Accumulation of Radioactive Substances in Aquatic Forms," Proceedings of the International Conference on the Peaceful Uses of Atomic Energy 13 (P/280): 364-367 (1955).

21. Davis, J. J. and R. F. Foster, "Bioaccumulation of Radioisotopes Through Aquatic Food Chains," Ecology 39 (3): 530-535 (July, 1958).

22. Davis, J. J., R. W. Perkins, R. F. Palmer, W. C. Hanson, and J. F. Cline, "Radioactive Materials in Aquatic and Terrestrial Organisms Exposed to Reactor Effluent Water," Second International Conference on the Peaceful Uses of Atomic Energy (1958). Paper No. 393.

23. Watson, D. G., L. A. George, and Patricia L. Hackett, "Effects of Chronic Feeding of Phosphorus-32 on Rainbow Trout," paper presented at International Congress of Radiation Research, Burlington, Vermont, August 10-16, 1958.

24. Whittaker, R. H., "An Experiment on the Relation of Phosphate Level in Water to the Removal and Concentration of Radiophosphorus," in "Biology Research - Annual Report 1953," Document HW-30437 (1954) (UNCLASSIFIED).

25. Davis, J. J. and C. L. Cooper, "Effect of Hanford Pile Effluent Upon Aquatic Invertebrates in the Columbia River," Document HW-20055 (1951) (SECRET) (Declassified with deletions 12-12-57).

26. Watson, D. G., "Chinook Salmon Spawning in the Vicinity of Hanford 1956," in "Biology Research - Annual Report 1956," Document HW-47500 (1957) (UNCLASSIFIED).

27. Hanson, W. C. and H. A. Kornberg, "Radioactivity in Terrestrial Animals Near an Atomic Energy Site," Proceedings of the International Conference on the Peaceful Uses of Atomic Energy 13 (P/281): 385-388 (1955).

28. Olson, P. A. and R. F. Foster, "Effects of Reactor Area Effluent Water on Chinook Salmon Fingerlings," in "Biology Research - Annual Report 1954," Document HW-35917 (1955) (UNCLASSIFIED)

29. Olson, P. A. and R. F. Foster, "Temperature Tolerance of Eggs and Young of Columbia River Chinook Salmon," Trans. Amer. Fish. Society 85: 203-207 (1955).

30. Olson, P. A., "Effect of Sodium Dichromate in Reactor Cooling Water on Young Chinook Salmon," Document HW-44357 (1956) (SECRET).

31. Foster, R. F., "The Effect on Fish of Increasing the Temperature of the Columbia River," Document HW-54858 (1958) (SECRET).

32. Foster, R. F., "Recommended Limit on Addition of Dichromate to the Columbia River," Document HW-49713 (1957) (SECRET).

33. Cline, J. F., A. A. Selders, and F. P. Hungate, "Chronic Effects of Reactor Effluent Water on Cereal Plants," in "Biology Research - Annual Report 1956," Document HW-47500 (1957) (UNCLASSIFIED).

34. Ewing, R. E., "Origin of Certain Radioisotopes in Hanford Reactor Cooling Water," Document HW-49485 (1957) (SECRET).

35. Healy, J. W., "Operation of Both Sides of Reactor Effluent Retention Basin," Document HW-31059 (1954) (SECRET).

36. Pendleton, R. C., "Contamination of River Organisms Grown in Retained and Non-Retained Reactor Effluent," Document HW-48381 (1957) (SECRET).

37. Palmer, R. F., "Chronic Build-up of Reactor Effluent Radioisotopes in Rats," in "Biology Research - Annual Report 1955", Document HW-41500 (1956) (UNCLASSIFIED).

38. Palmer, R. F., "Accumulation of Radioisotopes in Rats Chronically Exposed to Reactor Effluent Water," in "Biology Research - Annual Report 1956," Document HW-47500 (1957) (UNCLASSIFIED).

Waste Disposal Research and Development Program
B. Low and Intermediate Level Wastes
1. Surface Waterways

RADIOACTIVE WASTE DISPOSAL TO SURFACE WATERS**

by

E. C. Tsivoglou*

Introduction

The Public Health Service has conducted research and investigations on the pollution of surface waters since 1910, of for almost 50 years. Initially, these studies involved pollution by domestic sewage, but they were soon extended into the area of industrial waste disposal, and industrial waste studies presently comprise a substantial part of Service activities in water pollution research. The general industrial expansion of the past 30 years or so has been accompanied by a concurrent increase in the variety and complexity of industrial wastes, with the result that present workers in the field of waste disposal must possess a high degree of technical skill in one or more of a number of specialized areas. These include, for example, sanitary engineering, sanitary chemistry, aquatic biology, organic and nuclear

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chemistry, nuclear physics, toxicology, etc. All of these skills have been brought into play in recent studies by the Service. Only by such an assemblage of knowledge can we solve the waste disposal problems that we face in the complex industries of our modern society.

Control of the radioactive and toxic wastes that are produced by the nuclear industry is a problem in principle no different from the problem of controlling any other industrial waste. In essence, it requires determination of the effects of the waste discharge on downstream water uses, establishment of rational standards for the protection of legitimate water uses, and detection and regulation of waste discharges in specific cases. In the case of the nuclear industry, the fate of radioactive materials in the water environment and their effects on water use are not at present fully understood or defined. As a result, existing standards for the protection of surface waterways are regarded as temporary, rather than as firmly established criteria. They are subject to refinement and revision as more is learned about the fate of these materials in the stream and the effects of low level chronic human exposure to radiation. In many respects, however, control of these wastes is a simpler problem than is, for example, control of complex chemical wastes. In the case of radioactive materials there is a built-in highly specific tracer for which very specific analytical detection methods are available. In addition, there are definite limits for human radiation exposure that have been established by national and international scientific organizations, and these can be directly applied to specific problems.

Recent efforts of the Public Health Service on the nuclear waste problem have been directed toward development of detailed knowledge of particular waste sources, such as uranium refineries,[1] development of adequate waste detection methods, and investigation of the fate of specific nuclear and toxic wastes in the stream. Specific examples of this research effort will be detailed later.

As one of its functions in the water pollution field, the Service has for many years performed certain technical and consulting services in support of the various State pollution control programs and the related activities of local and other Federal agencies. Typically, at the request of a State or other agency, the Service has performed field and laboratory research on specific waste disposal problems that have general as well as local significance, and that add valuable information to our pool of technical knowledge. All of the required scientific specialties are brought to bear on such problems, thereby providing the necessary specialized knowledge and aid on an interim basis until the State agency can build its own competency and capability in the specific work. This kind of activity is typical of the development of the Service's program in the field of water pollution by radioactive materials.

As a part of this technical assistance, the Service maintains a highly developed training staff and presents short, intensive training courses in various aspects of water pollution control. For example, some 200 State, local, Federal, and industrial personnel have been given advanced training in the control of radioactive water pollutants, and an additional 250 have been trained in basic radiological health.

The Service also, when necessary, investigates and takes necessary action in cases of interstate water pollution in accord with its designated responsibilities under Public Law 660. In one such case involving pollution of an interstate stream by a uranium ore refinery, public hearings have been held, and field studies to evaluate the extent and effects of pollution are presently in progress. The States involved, and the U. S. Atomic Energy Commission, are cooperating in these studies.

Stream Significance

In most areas of the country sufficient water is not available for all desirable uses, and surface waters must, therefore, be used and reused for a number of purposes. A stream may in its course be used as a source of domestic water supply or as a source of industrial process water supply; it may provide water for the irrigation of croplands, as well as serving for commercial and sport fishing, stock watering, and recreation. The discharge to a stream of excessive amounts of any waste can seriously restrict or completely prohibit the use of the stream for other purposes. There are now available suggested Maximum Permissible Concentrations for radioactive materials in domestic water supply,[2] based upon the best existing information. If these concentrations are exceeded for extended periods of time, the water is considered unsafe for human consumption. However, these suggested standards do not necessarily protect the other uses of a stream. For example, many radioelements are concentrated and accumulated from water or from contaminated soil by green plants,[3][4] and irrigation water that contains radioactive material can result in crop contamination either directly or through the soil route. Regardless of drinking water tolerances, process

water for the photographic film industry and for food processing plants must be essentially free of radioactive contamination.

The aquatic life in a stream will also concentrate and accumulate radioisotopes,[5][6] and can thereby become unsafe for human consumption, or can even be directly damaged by radioelements present in the water. Studies of the aquatic life of the Columbia River,[6] for instance, indicate that radiophosphorus is heavily concentrated by plankton, algae, and fish - so much so that Foster and Davis[7] have stated: "If radiophosphorus were allowed to reach the maximum level permitted for drinking water, organisms living in the water would suffer radiation damage and the fish would be unsafe for human food."

Thus, the impact of radioactive waste discharges on a stream can be minor or great, brief or long in duration, depending upon the nature and quantity of waste, local water uses, stream hydrology, etc. In estimating allowable waste discharges from nuclear plants the effects on the total water environment and in the entire affected portion of the river basin should be considered, rather than taking a limited view of only one or two water uses that occur in a short river reach. Waste disposal is one recognized legitimate use of a stream, but it should not be practiced in such a way as to prohibit other desirable water uses.

Total Radiation Exposure

The fact that human populations may ingest or inhale radioactive materials in a wide variety of ways should also be recognized. In determining criteria for the safe disposal of radioactive wastes it is

important to consider all means by which the local population group is exposed to radiation. The effects of radiation exposure are cumulative, and the total exposure of a population is much more significant than the fraction associated with one particular source such as drinking water. A community may drink slightly contaminated water, eat slightly contaminated food, and breathe slightly contaminated air. A portion of the individuals may during their working hours ingest or inhale somewhat greater amounts of radioactive material as a result of their occupation in the nuclear industry. While any individual exposure, such as that due to drinking water, may be lower than the maximum allowable, the total radiation exposure may exceed that regarded as safe. It is the total exposure that has real significance, and it is important to examine each source, such as domestic water supply, in the light of the total radioactivity intake from all local sources. In this regard, some radioactive contamination of water, soil, fish, milk, etc., has resulted from the worldwide testing of nuclear weapons.[8][9] The resulting internal radiation exposure to people in any given area must be added to that which may come about because of local nuclear industries.

The basic principle of protection against human internal radiation exposure is to place an upper limit on the amount of exposure that can be allowed for the affected organ.[2] This has the effect of placing an upper limit on the total allowable intake of any particular radioisotope. Thus, for example, there is a recommended upper limit (the "Maximum Permissible Concentration") for the intake of strontium-90,[2] regardless of the path of entry; if the domestic water

supply were the only means of intake, then it could allowably contain as much strontium-90 as is specified by its particular Maximum Permissible Concentration for the general public.[2][10] If, however, there is appreciable intake of this radioisotope through milk and food, the allowable concentration in the domestic water supply must be reduced accordingly.

The same principles apply to combinations of radionuclides that affect the same organ.[2] Thus, because radium and strontium both affect the bones, they must be considered <u>together</u> as sources of internal radiation exposure, and the allowable intake of one is directly affected by the presence of the other. For instance, should a domestic water supply contain the maximum permissible amount of strontium-90, then no radium could be permitted in it, and vice versa; or if half of the allowable amount of strontium-90 were present, then only half of the Maximum Permissible Concentration of radium could be permitted. The intake of either by other paths such as food or milk would further restrict the allowable intake via drinking water. This illustration does not consider the possibility of synergistic effects of these radioelements.

<u>Control of Radioactive Wastes</u>

The proper control of radioactive waste discharges from any particular source is dependent upon other sources and types of radiation exposure, such as other nuclear industry, the extent of local environmental contamination by fall-out, available dependable dilution in the receiving stream, downstream water uses, etc. The presence of nuclear

weapons debris adds to both the difficulty and the expense of control of waste discharges from the nuclear industry. Significant variations in fall-out in the local environment would be expected to influence allowable industrial radioactive waste discharges. Because of the unpredictable nature of local fall-out, measurement of industrial waste discharges is more difficult and costly for both the regulatory agencies and industry - in many cases, it is becoming necessary to quantitatively detect specific radioisotopes, whereas simple gross radioactivity determinations might suffice were no fall-out present. However, even though there were no fall-out, the development of this problem would be only a matter of time as the nuclear industry expands and several such plants are located in the same river basin. In that sense, the experience in measurement that is being gained is of considerable value.

In speaking of radioactive waste control we are dealing with infinitesimal amounts of material. For example, the Maximum Permissible Concentration of radium in a domestic water supply is 4.0 micromicrograms per liter; for strontium-90, the figure is 80 micromicrocuries per liter, or about 0.5 micromicrograms per liter.[2] These figures may be compared to the allowable amounts of common poisons such as arsenic or lead in drinking water: for arsenic the allowable concentration is 50 million micromicrograms per liter; for lead it is 100 million micromicrograms per liter.[11] Thus, the allowable arsenic or lead content of drinking water is 10 million times the allowable radium content, and 100 million times the allowable strontium-90 content.

Conventional water treatment plants in use today are not designed to provide protection against such small concentrations of hazardous material, and treatment and control of these wastes at their source appears to be the only practical means of protection.

The foregoing comparison provides some indication of the magnitude of the problem of radioactive waste control, and of the care that should be exercised in dealing with this problem. In considering the control of human internal radiation exposure, the National Committee on Radiation Protection has stated the following excellent philosophy regarding radioactive waste discharges:

> "Because of the many uncertainties involved, this Committee recommends that every effort be made to keep the concentrations of radioisotopes in air and water and in the body to a minimum. The goal should be no radioactive contamination of air and water and of the body if it can be accomplished with reasonable expense and effort. If such a goal cannot be attained, the average operating levels should be kept as far below these recommended values as possible, and not above them for any extended periods of time."

Recent Research and Studies

Recent studies of radioactive water pollution by the Service have involved the development of analytical methods for detection and measurement of radioactivity and of specific radionuclides; field and laboratory investigations have been performed to determine the fate of radioactive materials in surface waters; studies of the chemical toxicity of wastes from the nuclear industry have also been carried out. In general, these

activities have had as their objectives the improved detection of radioactivity and the development of information to provide a basis for rational control of radioactive waste discharges.

Uranium Ore Refinery Wastes.[1][5][12] The uranium ore refining industry of the western United States has developed largely during the past decade. In these mills uranium is extracted from the raw ores, and concentrated. This product is then shipped to other installations for further refining, fabrication into fuel, and eventual use. There are at present fourteen operating mills, with capacities ranging from 300 to 3,300 tons of ore per day. Eight additional refineries are under construction or planned. Total capacity of the 22 mills will be about 20,000 tons of ore per day.

Radium is the most hazardous radioelement involved in waste discharges from the uranium mills. Uranium is the parent of a series of 14 radioactive isotopes that occur in nature. Only the uranium is desired, and, therefore, all of the daughter elements, including radium, thorium, bismuth, and others, are disposed of as wastes. While most of these radioactive wastes are retained in tailings ponds, or lagoons, some find their way into nearby streams.

Radium is a bone-seeking alpha emitter with a half-life of 1,620 years. It has the lowest of all of the MPC's for domestic water supply.[2] At present rates of ore processing, an estimated 3,000 grams per year of radium are discarded as wastes. In a short time, as the planned additional mills come into being, this figure will increase to about 5,000 grams per year. The bulk of this material, perhaps 98 to 99 per cent, is

generally retained in the tailings ponds as undissolved radium. However, the remaining dissolved portion, if discharged to surface waters, can constitute a significant stream pollution problem in terms of the concentrations generally regarded as safe.(2)(13)

In 1955, at the request of several State Departments of Health, the Service began a series of studies to evaluate the water pollution effects of waste discharges from the uranium mills.(12) At that time, a rapid reconnaissance field survey indicated that waste discharges from the operating mills contained from relatively little to considerable radioactivity. Samples of river water, river biota, river silts, and mill effluents were collected and analyzed for gross radioactivity and for radium. Water samples below several mills had radium concentrations somewhat in excess of the generally accepted standards, and several of the mill effluents contained more than allowable concentrations of dissolved radium. The biological samples (filamentous algae and bottom insects) appeared to indicate some concentration of radium, and mud samples showed considerably more than natural amounts of gross radioactivity. It was concluded that further study of these waste discharges was desirable.

One of the mills involved in the 1955 survey discharged all of its tailings, undissolved sands and slimes as well as liquids, to the nearby stream, and in 1956 a survey of this stream was performed.(5) This survey would, it was hoped, provide basic data regarding the fate of these wastes in the water environment, including data on the accumulation in stream biota and silts. About 60 miles of stream were surveyed over a two-week period. Water, biological, and mud samples were collected and composited,

and analyzed for radium as well as gross radioactivity. Two refineries discharged wastes to the stream. Water uses in the area included a domestic supply, irrigation, stock watering and recreation.

The water samples indicated a dissolved radium increase by a factor of about 100 immediately below each of the two mills. River muds collected below the mills had 1,000 to 2,000 times the natural background radium content. The river algae and bottom insects also showed increases comparable to the muds, and a few fish samples showed smaller but definite increases in radium content. The rib bones of a large fish showed a slight but definite radium gain above background levels. The stream below the mill that discharged all waste solids was essentially devoid of biological life for a distance of 10 to 15 miles. This was due to the blanket of sands and fine solids, rather than the radioactivity. Tap water samples at a small community using the river for domestic water had slightly more than the allowable dissolved radium content for general population exposure. Other water uses were not investigated at this time.

It was estimated that the dissolved radium discharges from the two mills were 0.3 and 2.6 milligrams per day. Undissolved radium discharged by the mills amounted to about 10 to 200 milligrams per day. The concentrations of radium in the three phases of the water environment, namely, water, mud, and aquatic life, decreased steadily proceeding downstream from the mills, due to additional dilution and dispersion. However, at no point did they again reach natural background levels.

Present studies of the uranium mill waste disposal problem include continued investigation of the fate of radium and other wastes in the stream environment, with emphasis on the effects on water use. In one locale an extensive field study is in progress with the objective of measuring, at least roughly, the total local human internal radiation exposure resulting from both uranium ore refining activities and fall-out. Representative environmental samples, including river water, river sediments, aquatic life, irrigated crops, farm topsoils, milk, precipitation, and treated community water supplies, are being analyzed for various components, including radium and radiostrontium. Within reasonable limits, this project should illustrate one approach to estimating the total internal radiation exposure from a study of the local environment. At the same time, in cooperation with the U. S. Atomic Energy Commission, the several States, and the industry, the Service has undertaken the development of an industrial waste guide for the industry.(1) This involves in-plant surveys of modern mill processing methods, with emphasis on following radium through the process, and analysis of the toxicity effects of other chemicals used. It is hoped that these studies will lead to the development of the most appropriate and economical waste treatment and disposal techniques, and that the resulting information will also be of assistance in site selection for new uranium refineries and similar industry

Columbia River Studies.(6) In cooperation with the U. S. Atomic Energy Commission and the States of Washington and Oregon, an extensive survey of the effects of radioactive waste discharges from the nuclear reactors at the Hanford Works of the Atomic Energy Commission on the

Columbia River was conducted by the Public Health Service during a two-year period from 1951-53. One of the principal objectives was to determine the effects of radioactive materials on the physical, chemical, and biological characteristics of these surface waters. Most of the work was confined to the area between Priest Rapids and Paterson, Washington, a section which includes the Hanford Works of the Atomic Energy Commission and McNary Reservoir, an impoundment created in late 1953. Limited studies were made also in Roosevelt Lake, Bonneville Reservoir, and the areas around Portland and Astoria, Oregon.

Cooling water for the reactors was pumped from the Columbia River, and given complete treatment, consisting of coagulation, settling, filtration, and chlorination, before use. After passing through the reactors, it contained radioisotopes (mostly short-lived) formed by the neutron bombardment of dissolved and suspended materials present in the water. Consequently, it was held in open retention tanks for a short period to permit decay of the short-lived activity. Following this brief holding period, the cooling water was discharged to the river. This effluent was monitored routinely. In addition, several thousand river water and aquatic biological samples were collected by a staff of ten men over the two-year period.

The highest gross beta radioactivity values for water and various aquatic organisms were found just below the reactor discharges. There was a fairly sharp decrease in radioactivity for about 25 miles and a constant but less sharp decrease thereafter. In the next 60 miles or so, values decreased to about one-tenth of those found just below the reactors.

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A measurable amount, somewhat higher than background, persisted to the mouth of the river at Astoria, Oregon, over 350 river miles below the reactors.

The accumulation of radioactive materials by aquatic organisms followed a definite pattern: plankton and filamentous algae, which absorb nutrients directly from the water, showed the greatest radioactivity per unit of weight; next were bottom animals which feed on this material, and then juvenile fish which feed on these animals; at the end of the chain were the adult fish which feed on juveniles. Exceptions to this general pattern were some of the fish which may shorten the chain by feeding directly on plankton, filamentous algae, or bottom animals. The principal radioisotope concentrated in aquatic organisms was P-32. For example, this was responsible for 90% or more of the activity in river fish, but less than 2% of the activity in the water.

The variations of activity in the Columbia River water were due primarily to changes in quality and quantity of cooling water discharges, dilution during seasonal high river flows, and radioactive decay of the isotopes present. In turn, the radioactivity in plankton and attached algae were directly dependent on levels in the river water. The maximum activity density occurred during low water stages and high water temperatures, usually in the late summer and fall.

Migratory fish such as salmon, the adults of which do not feed while in fresh waters, had very low activity at the same time that levels in actively feeding species, such as suckers, bass, and whitefish, were high.

The specific radioisotopes present are the major consideration in any such study. Maximum permissible levels are much higher for short-lived isotopes such as P-32, than for long-lived materials such as Sr-90 or radium. Radioactivity density levels of the order of magnitude found in the Columbia River water and aquatic organisms would be of utmost importance if derived from long-lived isotopes. The presence of only short-lived isotopes in the stream greatly reduced the potential hazard. However, the fact that some of the organisms (fish) may be used as human food was of some public health significance.(7)

Savannah River Studies.(14)(15) The Savannah River serves as the source of domestic water supply for the cities of Augusta and Savannah, Georgia, as well as providing the process water supply for the Savannah River Plant of the Atomic Energy Commission. Studies of the river quality were initiated and performed by the Service in cooperation with the U. S. Atomic Energy Commission and States of Georgia and South Carolina in 1951-52 and in 1955. The objectives of the early study were to evaluate the water quality characteristics of the stream, the background radioactivity of water and biota, and the ecology and economic importance of the biota, especially fish, before initiation of operations at the nuclear works and before impoundment of water at Clark Hill Dam.

Hydrological, chemical, physical, and biological characteristics of the stream were evaluated by these first studies, as well as radioactivity background levels. Types and populations of aquatic biota were observed and recorded, from plankton to fish. Neither commercial nor sport fishing constituted a major use of the upper river, but both types of fishing were

of greater importance in the estuary with shrimp and crab being utilized commercially. Organic pollution from Savannah and from upstream pulp and paper mills had considerable effect on the dissolved oxygen resources of the river, at times causing complete oxygen depletion downstream.

In 1955 further studies were conducted to evaluate the effects on the stream of operation of the Savannah River Plant and Clark Hill Reservoir. No major effects were observable, except that operation of Clark Hill Reservoir had stabilized stream flows and had reduced the turbidity of the lower river. No increased radioactivity of significance was found below the nuclear plant. Recreational fishing had apparently increased.

Since 1957 occasional water samples have been collected and analyzed on a routine basis for radioactivity. No significant change from the early background levels has been observed.

Ohio River.[16] At the request of the Ohio River Valley Water Sanitation Commission, brief radioactivity background studies were made of the main stem Ohio River and its major tributaries before initiation of operations at the Shippingport, Pennsylvania, nuclear power plant. The several States, the U. S. Atomic Energy Commission, and the industry cooperated in this survey. An initial evaluation of the radioactivity of water was made, and sampling locations and procedures discussed and established. Following this, routine stream monitoring was undertaken by the industry and the States. Consultative assistance was requested and provided to the Pennsylvania Department of Health and the U. S. Atomic Energy Commission on the problem of establishing specific waste control measures,

and information and assistance was provided regarding downstream domestic water supply intakes and emergency planning.

Tritium is an important waste product at the power plant, and in cooperation with the U. S. Atomic Energy Commission, the Service has undertaken research to establish an analytical method for determination of this radionuclide in stream samples. Following this, research on the fate of tritium in streams will be conducted.

Nonradioactive Wastes.[17][18] The production and use of atomic energy requires a vast complex of industrial operations, many of which produce wastes that have pollutional effects entirely apart from those due to radioactive materials. Such operations as uranium refining and processing, the preparation of fuel elements, the processing of spent fuel elements, and the processing of special materials used for reactor construction and moderation may produce wastes with significant pollutional effects even though containing little or no radioactivity. Some of these wastes contain materials that are toxic to aquatic life or that may impair the agricultural, industrial, or domestic use of surface waters. With the expansion of the power reactor industry, increased surface water temperatures may affect aquatic life. For instance, it has been estimated[6] that only a few degrees increase in the Columbia River water temperatures would seriously affect salmon runs. However, no such temperature rise has taken place in that case.

Chemicals such as chlorine, chromium, beryllium, uranium, vanadium, zirconium, mercury, organic solvents, ammonia, cyanides, thiocyanates,

fluorides, chlorides, nitrates, and sulfates may be present in wastes from various atomic energy operations. Some of these materials may be present in concentrations sufficient to adversely affect aquatic life, and studies have been made by the Service to evaluate the toxicity of many of these materials to fish. A bio-assay technique in which representative small fish are exposed to various concentrations of the chemical has been developed and used. Statistical analysis of the number of fish killed after a definite time at the various chemical concentrations yields a concentration safe for discharge to surface waters. Some of the chemicals, particularly the organic solvents, may taint fish even though they are not killed.

As examples of results, it has been found that ammonia and cyanides are highly toxic to fish, while nitrates, sulfates, and chlorides are relatively non-toxic. Metal salts are generally more toxic in soft than in hard water. Fluorides were relatively non-toxic, but appeared to have some chronic effect.

At the request of the U. S. Atomic Energy Commission and a State Water Pollution Control Board, studies were performed at a zirconium-hafnium separation plant.[18] These elements, which occur together in nature, must be separated during production of zirconium for reactor fuel elements, as hafnium is an undesirable constituent. The field studies indicated that the main pollutional effect was fish toxicity due to the presence of ammonium compounds. These studies resulted in the establishment of safe waste discharge rates in relation to stream flow.

The studies of toxicity of various chemicals to fish are a continuing research activity of the Service. As new chemical wastes are encountered in the nuclear industry, they will be evaluated by these tests.

Estuarine Problems. In connection with the development of nuclear powered vessels and nuclear operations near tidal estuaries, a number of requests for technical assistance have been received by the Public Health Service from various State and Federal agencies. The question of radioactive waste discharges in shellfish areas has been raised most frequently, along with the problem of analysis of estuarine samples. The high salt and natural potassium content of such samples makes the radioactivity analysis particularly difficult. In addition, available information regarding the characteristics of estuarine samples of various types is rather limited. Because of the expanding nature of this general problem, the Service has, in this case, provided what information and advice is possible, while at the same time initiating research in both analytical methodology and in the quality, types and characteristics of estuarine samples of water, biota, and sediments.

Studies at Oak Ridge National Laboratory. Since 1948 the Public Health Service staff at the Oak Ridge National Laboratory has worked with personnel of the Health Physics Division of the Laboratory in developing a program for the safe disposal of low level radioactive wastes, and especially in determining the efficiency of existing water treatment processes for the removal of those radioactive wastes which might find their way into streams that may be used as sources of water supply. Other agencies that have participated in these studies include the Tennessee Valley Authority, the Department of Defense and the U. S. Geological Survey.

As a result of the joint studies information has been made available on the efficiency of conventional water treatment processes for the removal of specific soluble radionuclides added to surface waters. The studies indicated that water treatment processes, in general, are not very effective for removing the more hazardous radionuclides, such as strontium, cesium, and iodine. To adequately remove these specific radionuclides, the existing processes would have to be modified, probably at considerable cost.

As an example of the results, Sr-90 might be considered. Coagulation with aluminum and iron salts resulted in the removal of only 5 to 10 per cent of the strontium isotopes. This efficiency could be increased somewhat through the addition of clay, as the strontium isotopes would be adsorbed on the clay. Filtration assisted in the removal of particulate activity which had not been settled out following coagulation. Conventional lime-soda ash water softening is somewhat more effective for the removal of the strontium isotopes, and through the use of excess amounts of the reacting chemicals strontium removals as high as 99 per cent were obtained. Ion exchange, also used for softening water, would be effective for the removal of strontium. By phosphate coagulation with careful control of pH and the calcium-to-phosphate ratio, 90 to 95 per cent of the strontium could be removed.

Since at best about 99 per cent of the strontium may be removed, the permissible concentration of strontium-90 in raw water would still be very low.[2][10] The only process that could dependably provide this degree of removal is ion exchange. Under emergency conditions, even though

very expensive, evaporation or distillation could be utilized for much higher removals. The sludges or residues resulting from any of these treatment processes must still be handled in a way to avoid exposure of operating personnel and the general public.

Because radionuclide concentrations are low and the concentrations of stable elements relatively very high, the task of separating radionuclides is not simple. As a result a substantial portion of the work on this project involved development of necessary analytical procedures for such constituents as radiostrontium, radioiodine, cesium-137, radiocobalt, etc.

The Service also participated in the studies on surface disposal of intermediate level wastes, particularly in defining the movement of these in the Conassuga shale indigenous to the Oak Ridge National Laboratory. The basic concepts of utilizing local soil for fixing radioactive materials and of utilizing the heat of radioactive decay for fusing the mixture into non-leachable ceramics were initiated under the direction of the Service.

Studies at Los Alamos Scientific Laboratories. In 1948 at the request of the Sanitary Engineering Branch of the Atomic Energy Commission, two Service specialists were assigned to the Los Alamos Laboratories for a five-year period to work jointly with personnel there to develop effective treatment methods for low-level laboratory wastes. However, the laboratory wastes were found to be extremely variable in flow rate and so complexed with cleaning compounds, etc., that special analytical procedures had to

be developed for plutonium-239 (the principal contaminant) before treatment processes could be evaluated. Following this, small batch studies indicated that the plutonium could be easily removed by biological treatment, but operational problems made it less attractive than coagulation with an iron salt and lime followed by sand filtration. This chemical treatment was tested in a full-scale pilot plant and proved successful, and the facility has continued to serve as a regular treatment plant since that time.

As certain of the laundry and organic wastes were not amenable to inexpensive chemical treatment, biological trickling filters with very high recirculation ratios were used to reduce the organic content and concentrate the plutonium in the secondary sludge. This led to the practice of mixing some of the low-level wastes with the local domestic sewage and treating it at the city trickling filter plant.

Flow and seepage studies made in the canyons receiving these wastes indicated that the stream did disappear and reappear on several occasions before it entered the water table in the Rio Grande River Valley. Fortunately, the local volcanic soil, tuff, has a great affinity for plutonium, so some of the activity was retained in the canyon receiving the liquid wastes.

Summary

Human populations may ingest or inhale radioactive materials in a wide variety of ways. In establishing criteria for the safe disposal of these materials, it is the total radiation exposure that must be considered rather than only a single path of entry such as a domestic water

supply. Because infinitesimal amounts of some radioelements are hazardous, control of radioactive liquid wastes at their source appears to be the only practical solution to the problem of safe radioactive waste disposal.

The Public Health Service program in radioactive liquid wastes research has been devoted largely to studies of the fate of radioactive materials in the water environment, especially insofar as these materials may impair or restrict legitimate water uses such as domestic and industrial water supply, irrigation, recreation, etc. Because of the relative newness of the nuclear industry, considerable effort to develop improved methods of detection of radioactivity has been necessary. Also, considerable emphasis has been placed by the Public Health Service upon measurement of the radioactive constituents in many types of environmental samples, in order to establish adequate information regarding existing levels of environmental radioactivity.

Bibliography

1. Tsivoglou, E. C., Kalda, D. C., and Dearwater, J. R. "Waste Characteristics for the Resin-in-Pulp Uranium Extraction Process." Proc. 1958 International Conf. on Peaceful Uses of Atomic Energy, United Nations (in press).

2. "Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water." Handbook No. 52, U. S. National Bureau of Standards, Washington, D.C. (1953).

3. Rediske, J. H., and Hungate, F. P. "Absorption of Fission Products by Plants." Proc. 1955 International Conf. on the Peaceful Uses of Atomic Energy, United Nations, 13, 354 (1956).

4. Chamberlain, A. C., Loutit, J. F., Martin, R. P., and Russell, R. S. "Behavior of I-131, Sr-89 and Sr-90 in Certain Agricultural Food Chains." Proc. 1955 International Conf. on the Peaceful Uses of Atomic Energy, United Nations, 13, 360 (1956).

5. Tsivoglou, E. C., Bartsch, A. F., Rushing, D. E. and Holaday, D. A. "Effects of Uranium Ore Refinery Wastes on Receiving Waters." Sewage and Industrial Wastes, August 1958 (in press).

6. Robeck, G. G., Henderson, C., and Palange, R. C. "Water Quality Studies on the Columbia River." U. S. Public Health Service, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio (1954).

7. Foster, R. F., and Davis, J. J., "Accumulation of Radioactive Substances in Aquatic Forms." Proc. 1955 International Conf. on the Peaceful Uses of Atomic Energy, United Nations, 13, 364 (1956).

8. Anderson, E. C., Schuch, R. L., Fisher, W. R., and Langham, W. "Radioactivity of People and Foods." Science, 125, 1273-78 (June 28, 1957).

9. Eckelmann, W. R., Kulp, J. L., and Schulert, A. R. "Strontium-90 in Man, II." Science, 127, 266-74 (Feb. 7, 1958).

10. "Maximum Permissible Radiation Exposures to Man." Insert to Accompany Nat'l. Bur. Stnds. Handbook No. 59, Nat'l. Bur. Stnds., Wash.,D.C. (1957).

11. "Public Health Service Drinking Water Standards, 1946." Public Health Reports, 61, No. 11, pp. 371-384; Reprint No. 2697 (March 15, 1946. Reissued March 1956).

12. Tsivoglou, E. C., Bartsch, A. F., Holaday, D. A., and Rushing, D. E. "Report of Survey of Contamination of Surface Waters by Uranium Recovery Plants." Public Health Service, U. S. Dept. of Health, Education, and Welfare, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio (1956).

13. "Part 20 - Standards for Protection Against Radiation." U. S. Atomic Energy Comm., Fed. Reg., 22, No. 19 (Tuesday, Jan. 29, 1957).

14. "Interim Report on the Savannah River Studies, July 1951-July 1952." Public Health Service, U. S. Dept. of Health, Education, and Welfare, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio. (1954).

15. "Interim Report on the Savannah River Studies, 1955." Public Health Service, U. S. Dept. of Health, Education, and Welfare, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio. (June 1, 1957).

16. "Progress Report of Radiation Background Survey of Waters of the Ohio River Basin." Public Health Service, U. S. Dept. of Health, Education, and Welfare, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio. (1956).

17. Henderson, D. R., and Tarzwell, C. M., "Bio-assays for Control of Industrial Effluents." Sewage and Industrial Wastes, 29, No. 9, 1002-1017. (Sept. 1957).

18. Palange, R. C., Henderson, C., Cohen, J. M., Shadix, C. N., and McDermott, G. N., "The Composition of Wastes from the Production of Hafnium-free Zirconium and their Toxicity to Fish." Report, Public Health Service, U. S. Dept. of Health, Education, and Welfare, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio. (Jan. 1955).

19. Tsivoglou, E. C. and Towne, W. W. "Sources and Control of Radioactive Water Pollutants." Sewage and Industrial Wastes, 29, No. 2, 143-56. (Feb. 1957).

Waste Disposal Research and Development in the Uranium Milling Industry

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INTRODUCTION

Prior to the discovery in May, 1957 that nitrate wastes from a uranium mill were percolating into the water wells around the plant, there had been little research or test work conducted on the treatment or disposal of deleterious wastes from the uranium milling industry. Efforts to treat the tailings had been restricted to impounding the solids and in some instances neutralizing the acid tailings. It had been recognized for some time that a prudent choice of processes for the uranium mill could affect the degree of pollution created by the mill. Two uranium mills, for instance, have since eliminated nitrate pollution through a change in process.

In July, 1957, however, a program was initiated at the Raw Materials Development Laboratory to investigate the extent of chemical pollution from the uranium mills and to develop means to alleviate the situation. Concurrently, some of the milling companies started programs of their own to investigate chemical pollution. At the same time, a program was initiated to evaluate the radioactive pollution problem and to develop means to reduce the activity of effluent liquors. The decision to study radioactivity in tailings followed the announcement of Mr. Charles E. Carl, Director, Division of Sanitary Engineering, State of South Dakota, that tailings from a uranium mill contained alpha and beta radioactivity several times in excess of the recommended maximum permissible concentration.

CHEMICAL POLLUTION STUDIES

As a means of determining potential chemical pollution problems theoretical effluent analyses were calculated from flowsheet material balances. These calculations were then verified, where possible, with results of assays from operating mills. As recorded in some detail in the report to the Joint Committee, under Part II of the Public Hearing on Industrial Radioactive Waste Disposal, the study showed existing chemical pollution and the potential for a great deal of additional pollution with the startup of additional mills. It was determined, more specifically, that iron, manganese, sulfate, nitrate, magnesium, uranium, chloride and total dissolved solids were potential pollutants.

A minor research effort was made in the laboratory to reduce the chemical pollution from uranium mills. The work centered on the effects of lime additions to combined acid and alkaline tails from a mill that employed both acid and alkaline leaching. It was determined from this test work that the neutralization of effluents with lime would greatly lower the concentration of some of the deleterious compounds. However, neutralization would not reduce all of the contaminants to specification levels, and some of the pollutants were unchanged by lime addition.

No reasonable procedure for removal of nitrate from tails was envisioned other than a process change which would eliminate nitrate as a reagent. No reduction of nitrate levels was achieved by lime addition. Solvent extraction or ion exchange procedures for scavenging nitrate from waste streams are too costly due to the relatively low concentrations of nitrate involved and the difficulty of recovering the nitrate in a usable concentration. Biological destruction of nitrate, possible through algae or aquatic plants, may be possible but would require a much more extensive investigation than was made. The few attempts made to reduce nitrate levels in pond solution by contacting with plant life indicated some effect, especially under anaerobic conditions, but excessive quantities of algae were required.

RADIOACTIVE POLLUTION STUDIES

The problem of eliminating radioactive pollution in uranium mill effluents has been investigated more thoroughly than the chemical pollution problem. Processes for solving the radium contamination problem have been developed in the laboratory, but before they will be reduced to practice they will have to be refined to the point of economic feasibility and tested on a pilot plant or plant scale.

PRELIMINARY SURVEY

The permissible levels for those elements which may be found in uranium mill waste streams, along with their half-lives and modes of emission are listed in Table I on the following page.

Table I

List of Potential Radioactive Contaminants in Uranium Mill Wastes

Isotope	Half Life	Radiation	Permissible Concentration Unrestricted Area 1/	
			μc/ml	dpm/l
U-natural		alpha	7×10^{-6}	1.5×10^{4}
Th^{234}	24.1 days	beta	3×10^{-1}	6.6×10^{8}
Th^{230} 2/	8.0×10^{4} years	alpha		
Ra^{226}	1622 years	alpha	4×10^{-9}	8.8
Rn^{222}	3.825 days	alpha	2×10^{-7}	4.4×10^{2}
Po^{210}	138.4 days	alpha	3×10^{-6}	6.6×10^{3}

1/ In this discussion radiochemical concentrations are presented in units of disintegrations per minute per liter, dpm/l, and microcuries per milliliter, μc/ml. The dpm/l units are convenient for expressing experimental data, but the Part 20 specifications are given in units of μc/ml. To convert dpm/l to μc/ml divide by 2.22 x 109, e.g., the specification for Ra^{226} is 8.8 dpm/l or 4.0×10^{-9} μc/ml.

2/ Not presently defined but is expected to be stated in the forthcoming new issue of Part 20.

In order to determine which radioactive isotopes were present in mill effluents in excess of permissible concentrations, samples of clarified tailing pond water from the various types of uranium mills were analyzed. These analyses are listed in Table II, from which it can be seen that the uranium concentration was too high in 2 out of 6 effluents, the radium specification was exceeded in all cases, the thorium -230 concentration was probably too high in 2 out of 5 cases, and the thorium -234 specification was not exceeded at all.

Table II

Analyses of Tailings Pond Effluents

	pH	U_3O_8 g/l	Tailings Effluent Analyses					
			Ra 226		Th 230		Th 234 + Pa 234	
			µc/ml	dpm/l	µc/ml	dpm/l	µc/ml	dpm/l
1.	1.5	0.10*	4.0×10^{-6}*	8,900	3.9×10^{-5}	85,000	1.2×10^{-4}	270,000
2.	3.3	0.0034	5.4×10^{-6}*	11,800	1.2×10^{-6}	2,600	4.8×10^{-6}	10,500
3.	7.7	0.0003	3.3×10^{-7}*	716	2.8×10^{-8}	61	1.8×10^{-7}	404
4.	6.9	0.02*	8.1×10^{-8}*	178	9.4×10^{-8}	206	5.1×10^{-6}	11,320
5.	9.9	0.009	2.0×10^{-6}*	4410				
6.	2.0	0.002	2.7×10^{-6}*	5960	1.1×10^{-5}	24,700		

Mill Processes:
1. Acid Leach - Solvent Extraction
2. Acid Leach - RIP
3. Acid Leach - RIP
4. Combined Acid Leach - RIP and Alkaline Leach - Precipitation
5. Alkaline Leach
6. Acid Leach - CCD - Solvent Extraction

* Specification exceeded

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ACID PLANT EFFLUENTS

In attempting to find a solution to this problem, the possibility was explored of removing the radioactive isotopes from solution by coprecipitation or adsorption on a solid material. It was found that neutralization of acid tailings removes a great deal of radioactivity. When gypsum, ferric hydroxide, and other basic salts are precipitated from acid tailings by neutralization a gross decontamination is achieved by the coprecipitation of the radioactive isotopes. A more specific means was discovered for removing radium, the worst radioactive offender, from solution. When acid tailings were contacted with the insoluble mineral barite (natural barium sulfate), quite effective removal of radium was achieved by adsorption onto the barite. The barite would then be removed from the solution by various clarification techniques and impounded.

As a result of this preliminary survey of the problem it appeared that a two-step process consisting of neutralization and barite treatment might prove effective for eliminating radium and other radioactive isotopes from acid mill waste solutions. The efficiency of this process and the variables which affect the neutralization and barite treatment were examined in some detail in the laboratory.

One of the first variables considered was the effect of various amounts of ore solids in the tailings solution to be treated. A study was made to determine what effect the presence of slimes in the tailings would have on the amount of radium removed from solution by neutralization. It was determined that neutralization of the mixture of ore pulp and solution which constitutes the whole mill tailings resulted in a 10-fold decrease in soluble radium concentration. If the mixture of solids and solution was discharged to a tailings pond and only the clear overflow was treated by neutralization, a 500-fold decrease in soluble radium concentration resulted.

A series of comparison tests was made in order to define which of the common alkalies was the most efficient and economical. Tests were made with calcium hydroxide, calcium carbonate, ammonium hydroxide and sodium hydroxide at pH levels in the range of 3 to 9. These tests, performed to compare the efficiency of various caustics, showed that calcium carbonate and calcium hydroxide are slightly more efficient in the pH range of 3 to 8 than ammonium and sodium hydroxide. Since the calcium reagents are the cheaper, they are the obvious choice for neutralizing acid mill effluents.

The important variables examined in regard to the barite treatment process were concentration, particle size, purity, influence of radium concentration, contact time, and method of contact between tailings solution and barite. It was determined that for treating neutralized acid tailings commercially available grades of barite provided the desired decontamination at a concentration of 5 to 10 pounds per ton of solution for a single stage of contact of about one hour. The exact amount of barite required to achieve the specification levels of radium in any particular number of contacts is determined by the level of radium pollution since an equilibrium was shown to exist between the amount of radium adsorbed per unit weight of barite and the amount of radium in solution.

The barite used in most of the laboratory tests is material used by the petroleum industry for weighting purposes in drilling muds. This material is 85 to 90 per cent barium sulfate and is 80 per cent -325 mesh. A reasonably practical process in the economic sense would be limited to the use of about 2 pounds of barite per ton of waste solution. A limited amount of process work done to date has indicated that if the contact between the neutralized tailings and the barite is made in a countercurrent contact process, the desired level of radium will be approached but not fully realized at concentrations of 2 pounds per ton of solution. Certainly, for single batch contacts the concentration of 2 pounds of barite per ton of solution is not sufficient.

ALKALINE PLANT EFFLUENTS

The volume of tailings being discharged from acid leach mills is much greater than that leaving alkaline leach mills, and processes for treating acid tailings are probably more urgently needed. However, laboratory investigations have been conducted to determine means of decontaminating alkaline tailings. This work has been centered on treating the tailings from the mill at Monticello, Utah, which is owned by the U. S. Atomic Energy Commission.

The variables involved in treating alkaline tailings are similar to those previously discussed for acid tailings. Barite may be used to adsorb radium from solution. Clarification of the tailings is required for effective utilization of the barite. In this case, clarification is difficult to achieve by simply allowing the solids content of the tailings to settle out in a pond since in this alkaline solution settling rates are very slow. Flocculating agents, such as filter alum (aluminum sulfate) and copperas (ferrous sulfate), which are commonly used in municipal water treatment plants, may also be used

for clarifying murky alkaline tailings at a very reasonable cost. While the original purpose in clarifying alkaline tailings was to provide a clear feed for barite treatment, it was found that some decontamination was also realized in the clarification step.

Neutralization of alkaline tailings prior to barite treatment is also beneficial. In this case, the alkalinity is decreased from a pH of about 10 to a pH of 8.5 to 9 by addition of sulfuric acid. No precipitate is formed in the solution and the radium level is unaffected, but a higher decontamination is achieved by barite treatment in the neutralized solution.

Again it was found that the amount of barite required to decrease the radium concentration to the specification level depended on the type of contact made between the tailings and the barite. Countercurrent contact in two stages after clarification and neutralization indicated that about 2 to 5 pounds of barite per ton of solution would be sufficient. Approximately the same requirements were indicated for a process involving two successive contacts with fresh barite. Finally, it has been shown in laboratory tests that percolating the neutralized alkaline tailings through a bed of fine mesh barite promises to be the most efficient method of contact. Barite requirements on the order of 0.5 pound per ton of solution are indicated.

SUMMARY

The laboratory data to date has indicated that both acid and alkaline tailings may be decontaminated by a neutralization-barite adsorption process. However, to meet the extremely stringent specifications as detailed in Part 20 it may be necessary to add a costly amount of chemical reagents or go to relatively complex contacting schemes for applying the process. At the present time, further laboratory experiments are in progress to refine the basic process. Improvements which will result in practical costs to the mills are needed.

Along with developing at least some of the fundamental process data for handling the problem, it was necessary to develop methods for detecting and quantitatively determing the radioactive isotopes. Methods for determining uranium, radium-226, thorium-234, thorium-230, and polonium-210 are now available to the mill operators.

Finally, surveys of typical mills are being made in order to trace the flow of radium through the process in an effort to determine the effect of the uranium treatment process on the dissolution and ultimate disposition of radium.

BIBLIOGRAPHY

1. Whitman, A., and Porter, E. S., "Chemical Stream Pollution from Uranium Mills," U. S. Atomic Energy Commission Report, WIN-99, (June 13, 1958).

2. DeSesa, M. A., "Interim Report on Investigations in to the Problem of Radioactive Pollution of Uranium Mill Effluents," U. S. Atomic Energy Commission Report, WIN-101, (December 15, 1958).

3. Whitman, A., and Beverly, R. G., "Radium Balance in the Monticello Acid RIP Uranium Mill," U. S. Atomic Energy Commission Report, WIN-113 (December 30, 1958).

4. Beverly, R. G., "Survey and Prevention Techniques for Control of Radioactivity Hazards at the Monticello Uranium Mill, U. S. Atomic Energy Commission Report, WIN-114 (December 15, 1958).

5. The New Mexico Department of Public Health, "Report on an Investigation of Ground Water Pollution; Grants-Bluewater, New Mexico" (August, 1957).

6. Public Health Reports, "Public Health Service Drinking Water Standards, 1946" 61, No. 11, p. 371 (March 15, 1946).

7. Betz, W. H., and Betz, L. D., "Betz Handbook of Industrial Water Conditioning," Philadelphia, Pa., p. 236 (1953).

8. Klein, L., "Aspects of River Pollution," Academic Press (1957).

9. Rudolff, W.,"Industrial Waste," Reinhold Publishing Co. (1953).

10. "Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water," Handbook 52, U. S. Department of Commerce, National Bureau of Standards (March 20, 1953).

11. "Regulation of Radiation Exposure by Legislative Means," Handbook 61, U. S. Department of Commerce, National Bureau of Standards, (December 9, 1955).

12. "Standards for Protection Against Radiation," Part 20, Chap. 1 Atomic Energy Commission, Title 10 - Atomic Energy, No. 19, Vol. 22, Federal Register, (January 29, 1957).

13. "Water Quality Criteria," State Water Pollution Control Board, Sacramento, California.

REMOVAL OF RADIOACTIVE CONTAMINATION FROM PUBLIC WATER SUPPLIES

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Research was begun in 1949 at the Sedgwick Laboratories of Sanitary Science of the Massachusetts Institute of Technology on the effectiveness of conventional water treatment processes in the removal of radioactive contamination from public water supplies. This work was done under Contract No. AT(30-1)-621 with the U.S. Atomic Energy Commission. Laboratory research was conducted on waters containing such radioactive and stable isotopes as strontium, yttrium, iodine, phosphorus, cobalt, and ruthenium. This work was followed by field studies on actual water filtration plants having surface water sources contaminated with small amounts of radioactive fallout during and following the nuclear weapons testing program held in Nevada during the early part of 1955. Information developed during this program is currently (1959) being utilized by the M. I. T. staff in the continuing analysis of the water supplies of the City of New York so that the work could be considered as still in force.

Many reports and technical papers have been made available to the Atomic Energy Commission, the U.S. Public Health Service and to the waterworks industry as a result of this research program. A brief summary of these reports will serve to indicate the scope of the research and the significance of its findings.

Removals of radioactive anions by the standard water treatment processes of coagulation, sedimentation and filtration were studied by Kaufman, Thomas and Goldman (1)(2)(3)(4). Special attention was paid to phosphate removals as radioactive phosphorus has been identified as a product of water-cooled reactors under certain conditions. Fundamental studies had to be

made of the mechanism of phosphate removal by coagulation in the presence of various constituents of natural waters. It was shown that removals greater than 90 percent could be achieved by efficient coagulation and settling followed by rapid sand filtration. This is of genuine significance to municipal water officials because it shows that with their filtration plants being maintained at peak efficiency, or modernized to attain such efficiency, high removals of radioactive soluble phosphates can be achieved.

Nesbitt (5)(6) and his colleagues investigated the removal of strontium by conventional water treatment processes. The purpose of these studies was to determine whether modern water filtration plants, such as those in Philadelphia, Washington, Cleveland, Chicago and Denver, and many other cities using surface water supplies, could remove strontium-90. This is one of the most dangerous radioactive elements because it is a bone-seeker, like calcium, in the human body. The results showed that municipal and industrial water filtration plants could be modified at minimum cost to remove strontium successfully. Coagulation with phosphates rather than alum can be done at any plant to achieve a strontium removal approaching 90 per cent. For higher removals the filtration plant would have to be modified to provide a two-stage system wherein excess phosphate is precipitated by calcium and strontium in the second stage. (See Fig. 1.)

McCauley (7)(8) investigated the use of lime-soda softening plants for the decontamination of radioactive water supplies. Particular attention was paid to the determination of the ability of typical softening plants in removing radioactive strontium. It was shown that the mechanism by which strontium was coprecipitated with calcium carbonate in lime-soda softening was determined to be one of mixed crystal formation. This study was made by use of the principles of physical and crystal chemistry and by X-ray diffraction. These methods showed that this mixed crystal coprecipitation was characterized by: (a) increased per cent removal of the coprecipitated strontium was noted with an

FIGURE 1. Experimental water filtration plant for decontamination of radioactive waters in the laboratories of the Massachusetts Institute of Technology.

increasing per cent removal of the calcium ion which it replaced in mixed crystal formation, (b) uniformity of the per cent removal of the strontium ion was observed with varying concentrations of stable strontium and, (c) a straight line variation occurred in one of the lattice constants of the precipitated calcite crystals with increasing concentrations of strontium in the treated waters. Two technical papers in the Journal of the American Water Works Association resulted (9)(10) from these studies and disclosed a method of repeated precipitation which could be adapted to two-stage municipal water softening plants to remove radio-strontium with lime. It was shown possible to reduce strontium-90 activity from a relatively high value of 200 counts per second or higher to counts near background, or 99 per cent removal. This was a new process developed as a result of this research project and applicable to the solution of certain decontamination problems of municipal and industrial water softening plants.

The foregoing research projects were concerned with the removal of soluble radioisotopes from water. When radioactive fallout from nuclear weapons testing is involved, as it has been in limited quantities in past years in many surface water supplies of the United States, the removal of radioactive particulate matter is also of importance. This is especially true for the paper and photographic industries. Burbank (11)(12) studied the removal of particulate matter from water supplies by coagulation and the characteristics of fallout. It was found that if rainfall occurs within 30 days of a blast, 60 per cent of the radioactivity will be in particulates and 40 per cent in the soluble state in the rain. However, if rain is delayed at any point for a period considerably longer than 30 days, over 80 per cent of the radioactivity will be dissolved in the rain. The size range of particulates was shown to be from 5 millimicrons to 11 microns, with a mass median size just below 2 microns. These results delineated the problem confronting water works officials.

Studies were conducted on the removal of contamination from typical waters from several parts of the United States: New England, Midwestern, Southwestern and Northwestern. Processes for softening and/or removal of turbidity or color from waters both demonstrated capabilities in the removal of fallout particles. These served as nuclei for alum or lime floc and thus were removed from the water in the coagulation process. Results showed that removals of 15 to 50 per cent of particles having sizes from 0.5 to 3 microns was accomplished in the low turbidity New England and Northwestern waters. With Midwestern waters which were both turbid and hard, removals of these fallout particles by the softening and clarification process were better than 95 per cent.

The Southern waters are characterized by high turbidity and medium hardness in some instances. With alum and chlorinated copperas over-all removals of particulate fallout range from 70 to 98 per cent in all size ranges from 0.5 to 10 microns. Softening with lime and soda ash gave removals between 73 and 99 per cent in size ranges from 2 to 10 microns but was not as successful with smaller particle sizes in the range from 0.5 to 1.5 microns. It is essential to know the characteristics of the particles in the water supplies and the ability of existing treatment plants to accomplish high degrees of removal. These experiments have served to indicate the need for efficient operation of municipal and industrial water plants to assure maximum removals of particulate fallout.

In order to put these laboratory findings into practice, an extensive survey was made of water treatment plants located throughout the country to determine the removals of fallout debris which could be obtained during routine operations when the incidence of fallout was higher than normal. These tests were made during the 1955 series of continental weapons tests in Nevada. The locations of the plants were based on having open reservoirs which would

have a probability of being on one or more of the predicted paths of air masses carrying nuclear debris from the Nevada test site. The plants were also chosen on the basis of the type and source of water available, making it possible to obtain samples of raw and treated water when using alum, ferric hydroxide, lime softening and ion exchange in their treatment processes. The locations of the plants were as follows: Akron, Ohio; Cambridge, Massachusetts; Ely, Minnesota; Twin Falls, Idaho; Chapel Hill, North Carolina; Chicago, Illinois; Detroit, Michigan; Fayetteville, Arkansas; Flint, Michigan; Grand Forks, North Dakota; Great Falls, Montana; Green River, Wyoming; Knoxville, Tennessee; Lexington, Kentucky; Mitchell, South Dakota; Oshkosh, Wisconsin; Raton, New Mexico; Rochester, New York; Spartanburg, South Carolina and Springfield, Illinois.

The results from each of these plants were published (13), together with the results from a similar study in a system without a treatment plant, that of Portland, Maine, (14). It was found that the removals of gross beta contamination representing soluble and particulate fission product debris, averaged from 50 to 75 per cent. There was a considerable variation in the results for any one day of operation at any one plant, but the type of treatment used and the characteristics of the raw water source appeared to have little effect on the efficiency of removal of the radioactive contamination. In other words, all treatment plants were capable of securing better than 50 per cent removal. These field results were reassuring because in no instance was any dangerous level of radioactivity reached in municipal water supplies as the result of fallout from the nuclear tests. Close control of chemicals and operating procedures were necessary to assure higher removals. These results will serve as guides for the water works industry in determining procedures which can be developed as the result of laboratory studies because there was good coordination between laboratory and field results in the study

supervised by the personnel of the M. I. T. project.

Other problems pertaining to surface water supplies arose during the course of the investigation and had to be pursued by the research personnel. One of these was an investigation of assaying techniques for radioisotopic contaminants in water supplies conducted by Wheler (15)(16). The primary objective of this research was to determine whether tolerance amounts of beta activity, of the order of 10^{-7} microcuries per milliliter, could be detected with standard laboratory end-window and windowless flow G-M counters. Minimum levels of detection, with no solids present, were established for a variety of radioisotopes which might occur in public water supplies. Out of this came a standardized method of assaying water supplies for beta activity. Thallium-204, a beta emitter with a reasonable average value for energy (0.783 Mev) was chosen as the standard for comparison with unknown sources of beta activity. Further development of radioassay techniques for water supplies was made by Nickerson (17). These techniques were used for the survey of many public water supplies in this research program.

The effect of beta radiation on biochemical oxidation of the organic matter found in polluted water supplies was also investigated by Skrinde, Sawyer, and Busch (18)(19)(20)(21). The purification action taking place in rivers such as the Ohio, the Mississippi and many other rivers receiving treated and untreated sewage, and later being used for water supplies, was simulated in the laboratory in order to determine effects of beta radiation on this purification. Using the manometric techniques of biochemical oxidation measurement, it was shown that radiophosphorus in concentrations up to 60 millicuries per liter had no significant effect upon the self-purification of the streams. This limit is far above that which could be tolerated by public water supplies. Therefore, the criterion of river contamination would be the

adaptability of the water for public consumption. This work was also corroborated by simultaneous studies using the standard biochemical oxygen demand techniques as approved by the American Public Health Association. It was necessary to develop more rapid methods for the determination of dissolved oxygen in simulated streams. The dropping mercury electrode and the polarograph proved to be an excellent means to carry out this study and assisted in reaching the final conclusions. The relationship of stream sanitation to radioactive wastes disposal was investigated by Butrico (22) and Busch (23). These workers investigated the many other sources of radioactivity from industry, hospitals, research laboratories and nuclear fuel processing plants as potential sources of contamination of public water supplies. The impact of these sources was reported to the water works profession (24) and to water filtration plant operators (25).

It will be noted from the references quoted at the end of this paper that a good number of scientific personnel were utilized in this work of investigating the decontamination of public water supplies by conventional water treatment processes. Many answers applicable to water works practice were arrived at through this research program. Not the least of the benefits derived from this research was the educational value of acquainting graduate students with techniques of assaying water for radioactivity, processes of water decontamination, and radioactive tracer work. These students took such a great interest in the work that many of them are now engaged in teaching others or in carrying out radiological health programs for governmental agencies. The following is a list of those who have been connected with this research project and are now engaged in radiological health work:

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REFERENCES

1. Eliassen, Rolf, Kaufman, Warren J., Nesbitt, John B. and Goldman, Morton I., "Studies on Radioisotope Removal by Water Treatment Processes, Journal American Water Works Association, Vol. 43, No. 8, August 1951.

2. Kaufman, Warren J., Nesbitt, John B., Goldman, Morton I. and Eliassen, Rolf, "The Removal of Radioactive Anions by Water Treatment", NYO 1571, September 1951.

3. Kaufman, Warren J., "The Removal of Radioactive Anions by Water Treatment", Sc.D. Thesis, Massachusetts Institute of Technology, 1951.

4. Goldman, Morton I., "The Removal of Radiophosphorus from Cambridge Tap Water by Coagulation and Sedimentation", SM Thesis, Massachusetts Institute of Technology, 1950.

5. Nesbitt, John B., Kaufman, Warren J., McCauley, Robert F. and Eliassen, Rolf, "The Removal of Radioactive Strontium from Water by Phosphate Coagulation", NYO 4435, February 1952.

6. Nesbitt, John B., "The Removal of Radioactive Strontium from Contaminated Water by Phosphate Coagulation", Sc.D. Thesis, Massachusetts Institute of Technology, 1952.

7. McCauley, Robert F., Lauderdale, R. A. and Eliassen, Rolf, "A Study of the Lime-Soda Softening Process as a Method for Decontaminating Radioactive Waters", NYO 4439, September 1953.

8. McCauley, Robert F., "A Study of the Lime-Soda Softening Process as a Method for Decontaminating Radioactive Wastes", Sc.D. Thesis, Massachusetts Institute of Technology, 1953.

9. McCauley, Robert F. and Eliassen, Rolf, "Radioactive-Strontium Removal by Lime-Soda Softening", Journal American Water Works Association, Vol. 47, No. 5, May 1955.

10. McCauley, Robert F. and Eliassen, Rolf, "Accelerating Calcium Carbonate Precipitation in Softening Plants", Journal American Water Works Association, Vol. 47, No. 5, May 1955.

11. Burbank, Jr., Nathan C., Lauderdale, Robert A. and Eliassen, Rolf, "A Study of the Removal of Radioactive Particulate Matter from Water by Coagulation", NYO 4440, September 1955.

12. Burbank, Jr., Nathan C., "Study of the Removal of Radioactive Particulate from Water by Coagulation", Sc.D. Thesis, Massachusetts Institute of Technology, 1955.

13. Lauderdale, Robert A. and Eliassen, Rolf, "The Removal of Radioactive Fall-Out from Water by Municipal and Industrial Water Treatment Plants", NYO 4441, March 1956.

14. Eliassen, Rolf and Lauderdale, Robert A., "Radioactive Fallout in Water Supply at Portland, Maine", Journal American Water Works Association, Vol. 48, No. 6, June 1956.

15. Wheler, Jr., A. Gordon, Kaufman, Warren J. and Eliassen, Rolf, "Assaying Techniques for Radioisotopic Contaminants in Water Supplies", NYO 4437, July 1952.

16. Wheler, Jr., A. Gordon, "Assaying Techniques for Radioisotopic Contaminants in Water Supplies", SM Thesis, Massachusetts Institute of Technology, 1952.

17. Nickerson, H. D., "Counting Technique for Determining Radioactivity in Surface Water Supplies", SM Thesis, Massachusetts Institute of Technology, 1956.

18. Skrinde, R. T. and Sawyer, C. N., "Effect of Beta Radiation upon Biochemical Oxidation in Polluted Waters", NYO 4438, September 1952.

19. Skrinde, R. T., "The Effect of Beta Radiation upon Biochemical Oxidation in Polluted Waters", SM Thesis, Massachusetts Institute of Technology, 1952.

20. Busch, Arthur N. and Sawyer, Clair N., "Application of the Dropping Mercury Electrode to B.O.D. Determinations", NYO 4436, May, 1952.

21. Busch, Arthur N., "Application of the Dropping Mercury Electrode", SM Thesis, Massachusetts Institute of Technology, 1952.

22. Butrico, F. A., "Disposal of Radioactive Wastes", SM Thesis, Massachusetts Institute of Technology, 1952.

23. Busch, Paul L., "Radioactive Waste: The Problem Posed", SB Thesis, Massachusetts Institute of Technology, 1958.

24. Eliassen, Rolf, "Significance of Radioactivity to Water-Works Superintendents", Journal of the New England Water Works Assoc., September 1952.

25. Eliassen, Rolf, "The Impact of Radioactivity on Water Works Practice", Journal of Maine Water Utilities Association, Vol. 31, No. 5, September 1955.

ABSORPTION OF CESIUM-137 BY COMPONENTS OF AN AQUATIC COMMUNITY

Robert C. Pendleton and Wayne C. Hanson*

Cesium-137, one of the more dangerous fission products in fallout, has been found in field crops (1), fish (2), dairy products (3, 4), human tissues (5), meats (6), phytoplankton (7), and wild fowl (8). Uptake of this radioelement from soil by plants is low (9, 10), but Klechkovsky (10) reported that when wheat was grown in nutrient culture solution the Cs^{137} content of the grain was over 4,000 times greater than from plants grown in soil containing this isotope. Hanson and Kornberg (8) found concentrations of Cs^{137} in flesh of waterfowl and aquatic food plants which were possible only if aquatic plants were capable of higher absorption coefficients than those reported for terrestrial plants.

This paper reports results of field studies and controlled experiments designed to test the hypothesis that a marked difference exists in the availability of Cs^{137} to ecologic chains originating in aquatic as compared with terrestrial environments.

Aquatic organisms were sampled in the field from a 1.1 hectare pond into which mixed fission elements from Hanford chemical separations facilities were released continuously in small amounts. Cs^{137} content of the organisms was determined by radiochemical analysis. The concentration of radiocesium in the water varied from 1×10^{-7} to 6×10^{-6} μc/ml. These studies were supplemented by a controlled experiment in which an aquatic community was established in a 675 square meter, concrete-lined pond. After a suitable period of acclimatization, enough radiocesium was added to produce an initial contamination level of 6×10^{-3} μc/ml.

ACCUMULATION OF Cs^{137} BY ORGANISMS

Concentration factors expressed as

$$\frac{Cs^{137} \text{ concentration in organisms}}{Cs^{137} \text{ concentration in water}}$$

were calculated from the mean contamination levels for both studies at a time when the Cs^{137} content of water and organisms had essentially stabilized (cross-hatched area, Figure 1). Concentration factors in field studies were

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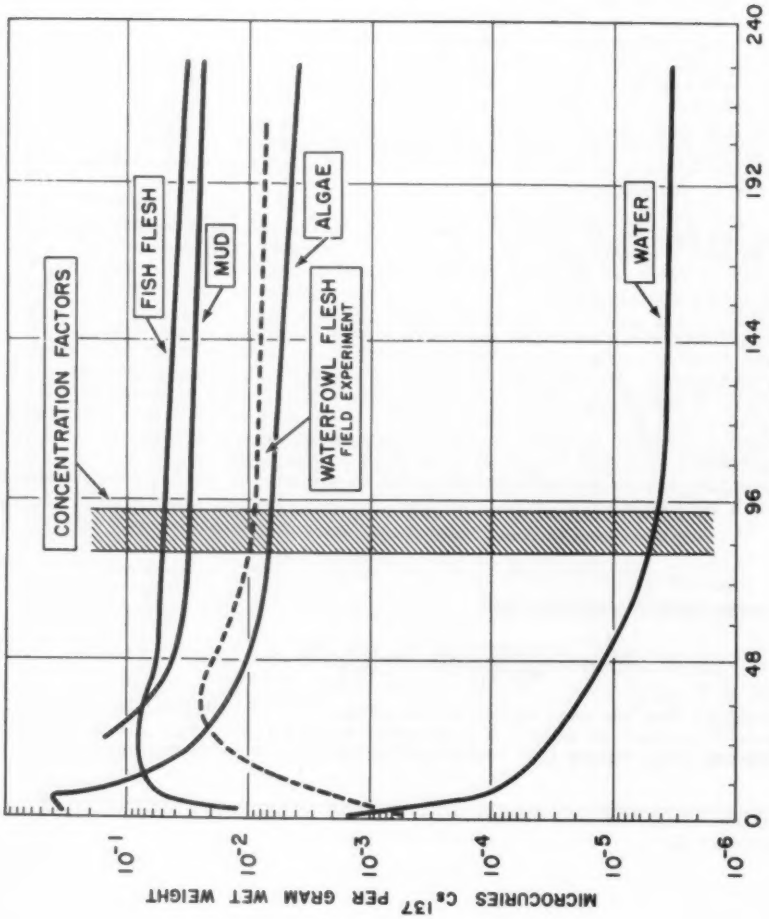

FIGURE 1. BIOACCUMULATION AND TRANSFER OF Cs^{137} BY COMPONENTS OF AN AQUATIC COMMUNITY

somewhat variable. This is attributed to fluctuation in the amounts of radioisotopes released into the pond and the varying lengths of exposure of waterfowl to contaminated food organisms. Waterfowl values in Figure 1 are based upon comparative amounts of Cs^{137} determined by radiochemical analyses of flesh of birds and in water collected at the same time. Zero time for the bioaccumulation of Cs^{137} by waterfowl was considered coincident with the arrival of migrant birds. Sampling was confined to a group of species representing several trophic levels[1] and a food chain through which Cs^{137} could be transferred directly or indirectly to man.

All the organisms exposed to Cs^{137} accumulated the isotope in amounts which were significantly higher than the water. Concentration factors for Cs^{137} in organisms, food web positions, and trophic levels for representative organisms are presented in Table I.

TABLE I

Concentration Factors for Cs^{137} in Aquatic Organisms

Organism	Concentration Factor		Food Web Position
	Experiment	Field Studies	
Green Algae			Trophic Level 1 (Primary Photosynthetic Producers)
1. Rhizoclonium crassipelitum West and West	1,500-4,000		
2. Rhizoclonium sp.			
3. Oedogonium sp.		1,200	
4. Spirogyra sp.	400		
Submerged Seed Plants			
1. Water Weed (Elodea canadensis Michx.)	1,000		
2. Coontail (Ceratophyllum demersum L.)	400		
3. Sago Pondweed (Potamogeton pectinatus L.)	700		
Floating Plants			
1. Water Fern (Azolla filiculoides Lam.)	250		
2. Duck Weed (Lemna minor L.)	500		

FIGURE 1. BIOACCUMULATION AND TRANSFER

TABLE I (Continued)

Concentration Factors for Cs^{137} in Aquatic Organisms

Organism	Concentration Factor		Food Web Position
	Experiment	Field Studies	
Emergent Seed Plants			
1. American Bullrush (Scirpus americanus Pers.)			
Culms	50		
Seeds	300		
2. Hardstem Bullrush (Scirpus acutus Muhl.)			
Culms	90		
Seeds	400	70	
3. Cattail (Typha latifolia L.)			
Leaves	200		
Seeds	100		
4. Spotted Persicaria (Polygonum persicaria L.)			
Leaves	600		
Seeds	400		
5. Pale Persicaria (Polygonum lapathifolium L.)			
Seeds		240	
Herbivorous Animals			Trophic Level 2 (Primary Herbivorous Consumers)
1. Water Snail (Radix japonica Jay)	600		
2. Bullfrog tadpole (Rana catesbeiana Shaw)			
Entire	2,600		
Gut	4,500		
Flesh	1,000		
3. Spadefoot toad tadpole (Scaphiopus hammondi intermontanus)			
Entire	6,000		
4. Carp (Cyprinus carpio L.)			
Muscle	3,000		

TABLE I (Continued)

Concentration Factors for Cs^{137} in Aquatic Organisms

Organism	Concentration Factor		Food Web Position
	Experiment	Field Studies	
Carnivorous Animals			Trophic Level 3 (Secondary Predatory Consumers)
1. Damselfly Nymphs (*Ischnura* sp.)	800		
2. Dragonfly Nymphs (*Erythemis callocata* Hag.)	800		
3. Sunfish (*Lepomis gibbosus* L.)			Trophic Level 4 (Tertiary Predatory Consumers)
Adult, entire	7,500		
Muscle	9,500		
4. Bullfrog (*Rana catesbeiana* Shaw)			Trophic Levels 3, 4, 5 (Secondary, Tertiary, or Quarternary Predatory Consumers)
Muscle	8,000		
Omnivorous Animals			Trophic Levels 2 to 5 (Omnivorous Consumers)
1. Water shrimp (*Hyalella azteca* Saus.)	11,000		
2. American Coot (*Fulica a. americana* Gmelin)			
Muscle		1,800	
Liver		2,200	
Bone		800	
3. Common Mallard (*Anas platyrhynchos* L.)			
Muscle		2,000	
Liver		2,500	
Bone		700	
4. Ruddy Duck (*Oxyura jamaicensis rubida* (Wilson))			
Muscle		2,200	
Liver		2,800	
Bone		900	
5. Mixed Plankton Organisms (Net Plankton)	1,000-25,000		A melange of trophic levels

Algae and submerged seed plants generally had the highest concentration factors. The ability of algae to accumulate cesium in significant quantities has also been reported by Williams and Swanson (11). Herbivores ranged from one-third to several times as high as the algae on which they fed. Bioaccumulation by predatory insects did not equal that of vertebrate predators of the same trophic level. Vertebrate predators (trophic levels 3, 4, 5) usually had the highest concentration factors. These animals, which feed entirely upon other animal forms, concentrated Cs^{137} to higher levels than were found in their prey. The water shrimps were the only organisms which had a concentration factor higher than the predators. These crustaceans are voracious feeders upon a wide range of organisms, and may feed upon the largest plankton which, as a group, had a maximum concentration factor of 25,000.

SPECIES DIFFERENCES

Strong species differences in uptake were apparent among both plants and animals. Animal differences may be influenced by feeding rates and food preferences in addition to metabolic demand. Species differences in uptake of micronutrient elements have been reported from other studies (9, 12).

Submerged plants showed strong species differences which are probably a function of surface area. Rooted emergent plants also had different species uptake levels both in the field and experimental studies. Part of this difference may be attributed to availability, or root exposure to the water. Plants rooted in loose gravel accumulated more of the isotope than specimens of the same species which were rooted in mud.

The high concentrations in seeds were not in accord with studies on distribution of this element in plants grown in soils (9), but agree with results reported by Klechkovsky (10) for seeds from wheat grown in soilless culture. The high contamination levels in flesh of ducks (Table I) resulted from a diet of seeds rich in Cs^{137}.

RATES OF ACCUMULATION

Uptake in some species was explosively rapid, but others accumulated the isotope more gradually (Figure 1). Algae, snails, and tadpoles had accumulated Cs^{137} to over 100 times the content of the water after two hours of exposure. A considerable fraction of the Cs^{137} in snails and tadpoles at that time was presumably in the digestive tracts of the animals. Adult fish, frogs, and most seed plants had slower uptake rates. The ecological system as a whole, including inorganic surfaces, removed 95 per cent of the contamination in 50 hours and 99 per cent in five days.

Waterfowl sampling coincided with the arrival of migrant birds. Values in Figure 1 represent average amounts of Cs^{137} in a natural population of waterfowl including newly arrived unexposed birds, and subject to the departure of others exposed to the contamination for varying lengths of time. The slower attainment of maximum concentrations by waterfowl when compared

to fish is probably more apparent than real, because the selection of a base time for exposure of individual birds is discretionary. Maximum concentrations of Cs^{137} in flesh of waterfowl were in the range of 5,000 to 6,000 times that in water.

Inorganic surfaces took up a large part of the cesium as evidenced by the high concentrations in muds. The contamination level of mud declined steadily for about 45 days after which no significant changes appeared. It is probable that part of the Cs^{137} initially adsorbed on muds and other nonliving surfaces was not firmly bound. This loosely bound fraction was released to the water to become incorporated in the biomass as the water contamination declined. The truly adsorbed, or fixed fraction, was not released, and mud remained essentially stable throughout the remainder of the experiment.

Water contamination levels reached equilibrium after about 90 days. Some organisms continued to lose Cs^{137} throughout the experiment. The greater part of this loss was recycled into the increasing biomass, and a part was temporarily stored in the dead organisms that accumulated on the bottom of the pond.

SIGNIFICANCE OF RESULTS

These studies have demonstrated that plants exposed to Cs^{137} in an aquatic environment accumulated the isotope at least 500 times as much as reported (9) for plants grown in soils. Animals feeding upon these plants have a richer source of the isotope and become proportionately more contaminated than those receiving their foods through terrestrial food chains.

Hanson and Browning (13) showed that diving ducks (Oxyurinae), principally carnivorous forms, accumulated greater quantities of fission elements than puddle ducks (Anatinae) and coots (Rallidae) that fed mainly upon plants. All tissues of waterfowl had higher concentrations of Cs^{137} than the food organisms of the birds. Thus, radiocesium was further concentrated to a level exceeding the food content. This is in contrast with the discrimination factor reported by Libby (14) for Sr^{90}.

Assuming 100 per cent uptake (15, 16, 17), it is reasonable to conclude that a probable route through which Cs^{137} could be transferred to man in hazardous quantities is via food webs originating in aquatic environments as illustrated in Figure 2.

Disposal of Cs^{137} at the MPC level for drinking water (18) will produce hazardous levels of contamination in aquatic organisms which may be consumed by man. For example, carp, grown in water having an equilibrium level of 1.5×10^{-3} uc/ml Cs^{137}, may concentrate the isotope by a factor of 3,000 or 4.5 uc/g of flesh. Thus only 20 grams of this flesh might contain the equivalent of the long term maximum permissible body burden of 90 uc for man. Presumably, similar or higher quantities could be obtained from flesh of waterfowl or predatory fishes. Dairy products and meats from livestock that have access to aquatic vegetation from contaminated waters could contain high quantities of Cs^{137}.

The concentration of radiocesium in ponds which received low-level radioactive wastes from Hanford Operations was approximately 1/1000 of the MPC level for drinking water.

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[1] Organisms that obtain their food from plants in the same number of foodchain steps are in the same trophic level.

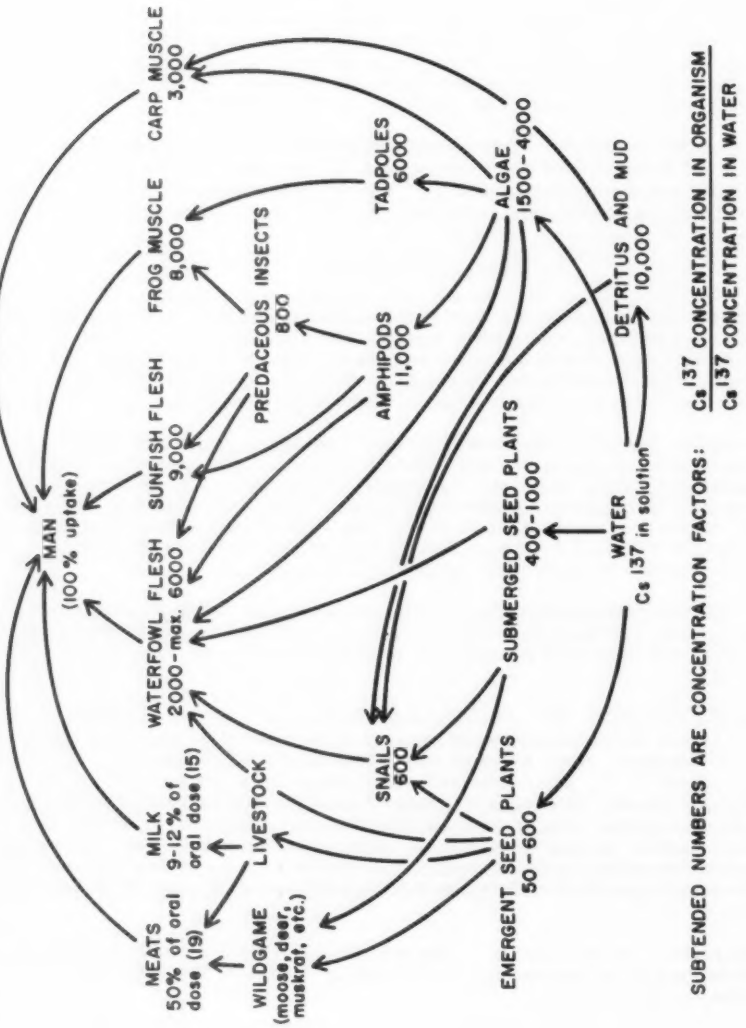

FIGURE 2. FOOD WEB THROUGH WHICH Cs-137 COULD REACH MAN

FIGURE 2. FOOD WEB THROUGH WHICH Cs137 COULD REACH MAN

REFERENCES

1. Clayton, C. G., Radioactive Contamination of Foodstuffs from Fall-Out as a Source of Error in Some Animal Experiments, Nature, 179:829-30 (1957).

2. Krumholz, Louis A., Observations on the Fish Population of a Lake Contaminated by Radioactive Wastes, Bull. Amer. Mus. Nat. Hist., 110(4): 277-368 (1956).

3. Booker, D. V., F. J. Bryant, A. C. Chamberlain, A. Morgan, and G. S. Spicer, Radiostrontium and Radiocaesium Measurement in Biological Materials to December, 1956, AERE - HP/R - 2182 (1956).

4. Booker, D. V., Radio-caesium in Dried Milk, Physics in Med. and Biol., 2:29-35 (1957).

5. Miller, C. E. and L. D. Marinelli, Gamma-Ray Activity of Contemporary Man, Science, 124:122-3 (1956).

6. Anderson, Ernest C., R. L. Schuch, W. R. Fisher, and W. Langham, Radioactivity of People and Foods, Science, 125:1273-8 (1957).

7. Davis, J. J., Dispersal of Radioactive Materials by Streams: with Special Reference to the Columbia River, in manuscript (1958).

8. Hanson, W. C. and H. A. Kornberg, Radioactivity in Terrestrial Animals Near an Atomic Energy Site, Proc. Intntl. Conf. Peaceful Uses of Atomic Energy, 13:385-8 (1956).

9. Rediske, J. H. and F. P. Hungate, The Absorption of Fission Products by Plants, Proc. Intntl. Conf. Peaceful Uses of Atomic Energy, 13:354-6 (1956).

10. Klechkovsky, V. M. (Ed.), On the Behavior of Fission Products in Soil, Their Absorption by Plants and their Accumulation in Crops, Acad. Sci. U.S.S.R. A.E.C.-TR-2867 (1956).

11. Williams, L. G. and H. D. Swanson, Concentration of Cesium-137 by Algae, Science, 127:187-8 (1958).

12. Beeson, K. C., V. A. Lazar, and S. G. Boyce, Some Plant Accumulators of the Micronutrient Elements, Ecology, 36:155-6 (1955).

13. Hanson, W. C. and R. L. Browning, Role of Food Habits in Wildlife Contamination at Hanford, Biology Research - Annual Report 1956, Document HW-47500, p. 201 (1957) (UNCLASSIFIED).

14. Libby, W. F., Radioactive Fallout, Proc. Natl. Acad. Sci. (U.S.), 43:758-775 (1957).

15. Univ. of Tennessee - AEC Agricultural Research Program, Quarterly Progress and Work Accomplishment Report for Quarter Ending June 30, 1952, ORO 77: 4-9 (1952).

16. Hood, S. L. and C. L. Comar, Metabolism of Cesium-137 in Rats and Farm Animals, Arch. Biochem. and Biophys., 45:423-33 (1953).

17. Hamilton, J. G., The Metabolism of the Fission Products and the Heaviest Elements, Radiology, 49:325-43 (1947).

18. Anonymous, Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water, National Bur. Standards Handbook, 52:16 (1953).

19. Ballou, J. E. and R. C. Thompson, The Long Term Retention of Cesium in the Rat Following a Single Intraperitoneal Injection, Document HW-46150 (1957) (UNCLASSIFIED).

RADIOACTIVE MATERIALS IN AQUATIC AND TERRESTRIAL ORGANISMS EXPOSED TO REACTOR EFFLUENT WATER

by

J. J. Davis, R. W. Perkins, R. F. Palmer, W. C. Hanson and J. F. Cline*

Water is commonly used as a coolant for nuclear reactors. Some are cooled with water which is pumped directly through the reactor. Others use the water in heat exchangers to control the temperature of a secondary coolant which is contained in a closed system that passes through the reactor. Water which has been forced through a reactor contains small amounts of many different radioisotopes from neutron-activation of dissolved minerals during normal operations. Fission elements may be produced if uranium is present in the water. Additional amounts of fission products may be present if ruptures occur in the coverings of fuel elements. Water discharged from the second type of cooling system does not contain radioactive materials except when leaks occur within the heat exchanger. Direct water cooling systems are used for reactors at the Hanford Atomics Products Operation. The Columbia River is the water source for these reactors and it is also the receptor of the reactor effluent.

Recently developed analytical techniques, based on gamma-ray and coincidence gamma-ray spectrometric methods of analyses[1] were used to qualitatively and quantitatively measure the radioisotopes in Columbia River water and in organisms which are exposed to it. These methods permitted the precise, sensitive, and rapid measurement of complex mixtures of radioisotopes without chemical separation in biotic samples. It was consequently possible to measure the uptake and distribution of trace amounts of both short-lived and long-lived radioisotopes in many organisms.

RADIOISOTOPES IN COLUMBIA RIVER WATER

More than sixty different radioisotopes have been identified in the effluent from Hanford reactors. Many of these isotopes have very

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short half-lives and are not detectable in the effluent at the time it is discharged into the river. Others which are initially scarce in the effluent are not detectable in the river water because of the tremendous dilution. Table I shows the concentrations of dominant radioisotopes in water collected during an average river flow period at a site known as Dot Island Station which is about 1.6 kilometers below the outfall of the reactor located farthest downstream.

Table I. Radioisotopes in Columbia River Water[a]

Isotope	Half-life	uc/ml
Na^{24}	15.06 hours	8.6×10^{-6}
P^{32}	14.2 days	2.4×10^{-7}
Cr^{51}	27.8 days	2.0×10^{-6}
Mn^{56}	2.58 hours	7.4×10^{-6}
Cu^{64}	12.8 hours	1.7×10^{-5}
Zn^{65}	245 days	8.9×10^{-8}
As^{76}	26.8 hours	1.9×10^{-6}
Np^{239}	2.3 days	9.7×10^{-6}

[a] Collected at Dot Island Station, September, 1957. Filtered through millipore filter. Raw water turbidity 4.0 ppm.

ACCUMULATION OF ISOTOPES BY INGESTION OF EFFLUENT

The Columbia River is a source of domestic water for several towns and cities located downstream from the Hanford reservation. In all cases the water is processed through standard water treatment plants before it is available to the public. The urban water pumping plant which is closest to the Hanford reservation is 61.6 kilometers downstream from the outfall of a reactor. The flow time between the outfall and the pumping plant varies during the year from eight to thirty hours. Much of the radioactive material which is discharged into the river is lost by radioactive decay during this time.

The potential hazards from drinking Columbia River water that contains trace amounts of radioisotopes have been determined both by theoretical evaluation (using the standards established by the International Commission on Radiological Protection, ICRP) and by laboratory experiments. The uptake and retention of the longer-lived radioisotopes in reactor effluent were studied with rats which were maintained with concentrated effluent water as their sole source of drinking water for periods up to one year. The average amounts of the radioisotopes that were measured in the bone and combined soft tissues of these animals, and estimates of the amounts of

isotopes consumed by the animals are shown in Table II.

Table II. Accumulation of Radioisotopes from Drinking Water by Rats

Isotope	Total amount consumed (uc)	Concentration in soft tissues[a] (uc/g)	Concentration in bone (uc/g)	Fraction of MPC for bone[b]
P^{32}	1.2	1.6×10^{-5}	8.5×10^{-5}	0.06
Sr^{89}	5.2×10^{-2}		1.9×10^{-6}	0.01
Sr^{90}	2.2×10^{-3}		8×10^{-7}	0.008
$Ba^{140}La^{140}$	$<2.2 \times 10^{-1}$	10^{-7}	2.5×10^{-6}	0.02
Cs^{137}		3.5×10^{-6}	4×10^{-6}	
Zn^{65}[c]	2.1	1.1×10^{-4}	6.2×10^{-4}	0.07
Rare Earths	4.4	7×10^{-7}	1.4×10^{-5}	0.13[d]

a Pelt and gastrointestinal tract not included.
b Maximum Permissible Concentrations (MPC) as established by ICRP for occupational exposure.
c Animals maintained on effluent for 347 days; other isotopes measured from animals which were maintained on same kind of water for 368 days.
d Total rare earth component assumed to be Cs^{144}-Pr^{144} for purposes of calculation.

As shown in Table II, the amount of each isotope accumulated was only a small fraction of the maximum permissible body concentration, even though the consumed water contained concentrations of the isotopes that were thousands of times greater than the Columbia River water. The highest fraction of MPC reported for the rare earth component is undoubtedly an exaggeration. This component was assumed to consist entirely of Ce^{144}-Pr^{144} because its actual isotopic composition was not known. This pair of radioisotopes which were chosen for calculations would produce a higher build up in the bone than any other combination of rare earth isotopes.

ACCUMULATION OF ISOTOPES BY TERRESTRIAL PLANTS

Of the thousands of square kilometers of land that are irrigated with water from the Columbia River, only a few receive water which is drawn from the river downstream from the Hanford reservation. The closest irrigation project pumps water from a site 46 kilometers downstream from the Hanford reactors.

Zinc-65 was found in all farm produce that was sampled from this land and small amounts of Cr^{51} and Sc^{46} were found in a few samples of vegetation. Examples of the concentrations of Zn^{65} that were found are shown in Table III.

Table III. Zinc-65 in Farm Produce[a]

Sample	uc/g	Concentration factor (uc/g wet wt of produce / uc/ml of water)
Pasture grass	8.29×10^{-5}	440
Beef steak	5.23×10^{-6}	28
Beef fat	1.48×10^{-6}	7.9
Milk	4.88×10^{-6}	26
Blackeyed peas	5.49×10^{-7}	2.9
Tomatoes	4.58×10^{-7}	2.4
Okra	3.94×10^{-7}	2.1
String beans	2.90×10^{-7}	1.5
Corn	1.56×10^{-7}	0.83
Grapes	8.9×10^{-8}	0.47
Irrigation water[b]	1.88×10^{-7}	

a Samples collected during summer, 1957.
b Sample not filtered.

The accumulation of Zn^{65} is undoubtedly associated with its long half-life and to the natural zinc deficiency of the soil in which the crops were grown. The comparatively high concentration of contaminants in the pasture grass was probably related to the manner of irrigation. The pasture land was watered by routine flooding which submerged the foliage and the garden crops were irrigated by rills. The concentration of radiozinc in milk is of particular interest. During mid winter, when the cow's diet did not include any foodstuffs that were grown on land of this irrigation project, the concentration of Zn^{65} in milk was about ten per cent of the value in Table III. The concentrations reported for beef steak and fat samples were from an animal which was butchered in late winter. The animal had been fed on radiozinc-free foodstuffs for four months prior to the time of butchering.

The uptake and translocation of radioisotopes by bean plants from undiluted reactor effluent water was studied by laboratory experiments. Culturing methods and nutrients used were as described by Rediske and Selders[2]. Table IV summarizes data for eight of the fourteen radioisotopes that were observed in plants which were grown in effluent solution for 14 days.

Crops of barley have been grown on the same plots irrigated with undiluted reactor effluent for six years. Grain harvested from the plots was used to replant the same plot the following year. There have been no effects from the radioisotopes in the effluent upon the productivity of the crops or the germination of the grain which was produced.

Table IV. Radioisotopes in Bean Plants Cultured for Fourteen Days in Reactor Effluent Containing Plant Nutrients.

Isotope	Half-life in days	Ave. conc.[a] in solution (uc/ml)	Per cent of[b] added isotope in leaves	Percent of[b] added isotope in stems	Percent of[b] added isotope in roots
P^{32}	14.2	1.26×10^{-5}	2.4	1.1	24.3
Sc^{46}	85		0.11	0.05	67.4
Cr^{51}	27.8	3.33×10^{-4}	0.11	0.08	29.8
Mn^{54}	310	4.6×10^{-7}		1.24	84.2
Co^{60}	1934.5	2.0×10^{-8}	1.0	0.26	19.7
Zn^{65}	245	1.28×10^{-5}	3.3	1.5	66.2
Ba^{140}	12.8	8.8×10^{-5}	1.7	0.61	55.3
Np^{239}	2.3	4.29×10^{-5}	0.13	0.01	33.1

a Each experimental group was grown in six liters of effluent solution. Fresh solution was supplied three times during the experiment.

b The average fresh weight total yields for leaves, stems and roots were 60, 29 and 75 grams respectively.

ACCUMULATION OF RADIOISOTOPES BY AQUATIC ORGANISMS

All aquatic organisms which inhabit the Columbia River downstream from the Hanford reactors contain concentrations of radioisotopes. Differences in the concentrations of total beta emmitters and of a few specific isotopes in different species of river organisms have been reported by Foster and Davis[3] and Davis and Foster[4]. The kinds and amounts of radioisotopes recently have been measured by better methods in many different kinds of aquatic organisms. The radioisotopic concentrations found in a few representative type of samples which were collected at Dot Island are given in Table V.

The tremendous bioaccumulation of different radioisotopes in organisms is demonstrated by comparison of the values in Tables I and V. Many of the isotopes found in the organisms were not measured in the river water because they occurred in amounts below detectable limits in the two-liter samples of water that were tested.

Comparison of the isotopic content of the various organisms from the same habitat indicated the effects of food habits, physiology and perhaps morphology upon the accumulation of radioactive contaminants by different species of plants and animals.

The algae, which derive their nutrients directly from the water, contained the most kinds and largest amounts of most isotopes that were accumulated by biological organisms. A considerable amount of the radioactive contamination which was measured from sessile algae was undoubtedly from materials adsorbed on their extensive surface areas. Similar

Table V. Radioisotopes in River Organisms Collected near Hanford Reactor[a]

Isotope	Physical half-life	uc/g wet weight					
		Green algae[b]	Sponge[c]	Insect larvae[d]	Snail[e]	Crayfish[f]	Minnows[g]
Na^{24}	15.06 hours	5.74×10^{-4}	7.28×10^{-4}	7.09×10^{-4}	1.77×10^{-3}	1.95×10^{-3}	1.13×10^{-3}
P^{32}	14.2 days	6.60×10^{-2}	4.46×10^{-3}	2.43×10^{-2}	1.44×10^{-2}	3.04×10^{-3}	2.40×10^{-2}
Sc^{46}	85 days	1.73×10^{-3}	9.47×10^{-5}	7.06×10^{-5}	2.88×10^{-5}		7.06×10^{-7}
Cr^{51}	27.8 days	7.90×10^{-3}	4.58×10^{-3}	6.00×10^{-3}	5.07×10^{-3}	4.82×10^{-4}	3.72×10^{-4}
Mn^{54}	310 days	1.03×10^{-3}		7.91×10^{-5}			
Mn^{56}	2.57 hours	8.22×10^{-2}	2.38×10^{-2}				1.87×10^{-4}
Fe^{59}	45.1 days	1.64×10^{-3}					
Co^{60}	5.3 years	1.55×10^{-4}	1.16×10^{-5}	1.72×10^{-6}	1.77×10^{-5}		
Cu^{64}	12.8 hours	1.13×10^{-1}	1.66×10^{-1}	7.10×10^{-3}	9.60×10^{-3}	5.14×10^{-4}	1.56×10^{-4}
Zn^{65}	245 days	1.23×10^{-2}	1.46×10^{-3}	1.98×10^{-3}	1.53×10^{-3}	3.65×10^{-4}	7.62×10^{-4}
As^{76}	26.8 hours	6.85×10^{-3}	6.32×10^{-3}	5.17×10^{-4}	1.00×10^{-4}	6.48×10^{-5}	1.73×10^{-4}
Zr^{95}-Nb^{95}	65.35 days	1.79×10^{-3}		6.63×10^{-5}			
Ru^{103}	39.8 days	1.22×10^{-3}		1.06×10^{-4}			
Ba^{140}	12.8 days	9.01×10^{-4}		4.22×10^{-5}	2.90×10^{-5}	1.88×10^{-5}	
La^{140}	40.0 hours	3.27×10^{-3}	1.23×10^{-3}	3.47×10^{-4}			
Ce^{141}	33.1 days	1.86×10^{-3}					
Np^{239}	2.3 days	2.69×10^{-3}	4.01×10^{-4}	3.11×10^{-4}			
Sr^{90}	19.9 years	2.07×10^{-4}	5.74×10^{-5}	1.21×10^{-5}			1.6×10^{-5}

a Organisms collected at Dot Island Station, August, 1957
b Stigeoclonium lubricum (Dillwyn) Kuetzing
c Spongilla lacustris (Linnaeus)
d Trichoptera: Hydropsyche cockerelli Banks
e Stagnicola nuttalliana (Lea). Shell not included.
f Astacus trowbridgii Stimpson
G Richardsonius balteatus (Richardson) Contents of alimentary canal not included.

concentrations were accumulated by phytoplankton. Extensive surface area probably also accounts, in part, for the large amounts of Mn^{56}, As^{76}, La^{140}, and Np^{239} that were associated with the sponge.

The effects of biological demand are indicated by the efficiency of the transfer of Na^{24} and P^{32} to the higher animals. Large amounts of both of these elements are metabolized by the organisms as is indicated by their mineral composition in Table VI.

Table VI. Mineral Composition of Columbia River Organisms[a]

	ppm of Ash					
Element	Green algae	Sponge	Insect larvae	Snail soft tissues	Crayfish	Minnows
Na	10,000	2,000	36,000	10,000	10,000	10,000
P	2,000	10,000	20,000	10,000	10,000	24,000
Cr	5	10	20	20	5	2
Mn	50	100	500	20	50	2
Fe	50,000	10,000 to 20,000	10,000 to 20,000	10,000	200	20
Co	<5	<5	<5	<5	<5	<5
Cu	100	1,000	500	200	500	100
Zn	<50	<50	<50	<50	<50	<50
Rare Earths	<20	<20	<20	<20	<20	<20
Ru	<20	<20	<20	<20	<20	<20
Ba	500	20	200	20	20	<5
Ce	<50	<50	<50	<50	<50	<50

[a] Species of organisms same as listed for Table V

Stable iron is abundant in all of the organisms. The radioactive isotope, Fe^{59}, which has a relatively long half-life occurred in substantial amounts in plankton and sessile algae. It seldom was found, however, in measurable amounts in organisms from higher trophic levels in the food web. Zinc is biologically essential as a trace element. Although its abundance in the organisms is much less than phosphorus, sodium or iron, the Zn^{65} was readily transferred through the food web and occurred in relatively large concentrations in almost all organisms sampled.

The radioisotopic concentrations of different tissues from adult Catostomid fish collected at the Dot Island Station during the month when highest contaminations occurred are compared in Table VII. The concentrations of different radioisotopes in specific tissues of the fish are associated with the stable isotopic composition and physiological functions of the respective tissues. Radioactive phosphorus was the dominant radioisotope in all tissues. It was most abundant in calcareous tissues,

f Astacus trowbridgii Stimpson
C Richardsonius balteatus (Richardson) Contents of alimentary canal not included.

Table VII. Radioisotopes in Tissues of Fish from Hanford[a]

Tissue	uc/g wet weight					
	Na^{24}	P^{32}	Sc^{49}	Cr^{51}	Mn^{54}	Fe^{59}
Bone	2.06×10^{-3}	4.64×10^{-2}			3.35×10^{-5}	
Scales	1.16×10^{-3}	2.80×10^{-2}		4.37×10^{-4}	2.08×10^{-5}	
Spleen	1.25×10^{-3}	1.57×10^{-2}	2.02×10^{-6}	3.64×10^{-4}		
Liver	2.85×10^{-4}	1.56×10^{-2}		4.02×10^{-4}	9.29×10^{-6}	
Kidney	9.47×10^{-4}	1.24×10^{-2}		3.75×10^{-4}	1.06×10^{-5}	
Gut	3.17×10^{-4}	7.34×10^{-3}	2.02×10^{-6}	9.54×10^{-6}	1.43×10^{-5}	2.59×10^{-5}
Heart	4.02×10^{-4}	7.18×10^{-3}		1.72×10^{-4}		
Ovaries	5.82×10^{-4}	6.81×10^{-3}				
Retina	1.37×10^{-3}	5.97×10^{-3}				
Blood	1.61×10^{-3}	5.62×10^{-3}	2.32×10^{-6}	5.39×10^{-4}		
Brain	1.06×10^{-3}	5.46×10^{-3}		1.01×10^{-4}		
Muscle	2.59×10^{-4}	2.82×10^{-3}	3.02×10^{-7}			
Skin	3.31×10^{-4}	2.80×10^{-3}	2.96×10^{-7}	6.28×10^{-5}		
Fat	2.55×10^{-4}	1.79×10^{-3}	1.29×10^{-6}	1.86×10^{-4}	3.36×10^{-6}	
Lens		1.79×10^{-3}				

Tissue	Co^{60}	Cu^{64}	Zn^{65}	Cs^{137}	Sr^{89-90} [b]
Bone		2.28×10^{-4}	3.13×10^{-4}		7.7×10^{-6}
Scales	1.46×10^{-6}	6.96×10^{-5}	7.74×10^{-4}		2.2×10^{-6}
Spleen	1.18×10^{-5}	2.79×10^{-4}	4.37×10^{-4}		-
Liver	1.71×10^{-6}	4.36×10^{-4}	2.79×10^{-4}		-
Kidney	6.70×10^{-6}	3.73×10^{-4}	4.33×10^{-4}		-
Gut	3.91×10^{-6}	1.13×10^{-3}	2.99×10^{-4}		-
Heart		8.39×10^{-5}	1.33×10^{-4}		-
Ovaries		1.45×10^{-4}	4.39×10^{-4}		-
Retina		5.75×10^{-4}	2.81×10^{-3}		-
Blood			2.87×10^{-4}		-
Brain		5.0×10^{-5}	8.99×10^{-5}		-
Muscle		5.54×10^{-5}	2.81×10^{-5}	9.0×10^{-7}	-
Skin		1.12×10^{-4}	6.51×10^{-4}		-
Fat	2.65×10^{-7}	1.93×10^{-4}	8.50×10^{-5}		-
Lens			8.26×10^{-5}		-

[a] Suckers, Catostomus macrocheilus Girard, collected at Dot Island Station, August, 1957.
[b] Bone and scales only tissue analyzed for Sr^{89-90}.

including scales and bone, which are high in phosphates and it is lowest in muscle and fat. Significant concentrations of Zn^{65} occurred in all tissues, with values for the retina and iris of the eye three or more times greater than in any other tissue. The avidity of Zn^{65} by these parts of the eye are undoubtedly associated with the high stable zinc content of these tissues[5]. The radiozinc content of the lens was comparable to its concentration in fat. The gut contained high concentrations of a melange of isotopes as would be expected from its digestive and absorptive functions.

The importance of the food web upon the accumulation of radioisotopes by organisms is demonstrated in Figure 1 which compares representative tissues from adult fish of different consumer or trophic levels. Inasmuch as all of these fish were collected at Dot Island Station at the same time, the differences in their radioactive contamination must result from their food habits and physiology. The suckers are the most radioactive species of large fish in the Columbia River. Their position in the food web is the second trophic level because they feed directly upon sessile algae. Whitefish represent the third trophic level. Their food consists primarily of immature herbivorous aquatic insects. Carnivorous squawfish belong to the fourth trophic level. Fish and crayfish are their main food items. The sturgeon is mainly a scavenger upon bottom debris.

The seasonal cycles of gross beta emitters in Columbia River fish have been discussed by Foster and Davis[3]. In brief, the contamination levels coincide with the water temperatures which, in turn, control metabolic rate. Comparison of data from fish collected at the Dot Island Station indicated that the concentrations of radiosodium and radiophosphorus decreased greatly during the winter but that the concentrations of radiozinc which has a long radioactive half-life remained relatively constant throughout the year.

ACCUMULATION OF RADIOISOTOPES BY WATERFOWL

The radioisotopic content in waterfowl which frequent the Columbia River below the Hanford reactors depends upon the food habits of the birds and the geographical areas of the river in which they feed. Contamination levels in tissues from a species of duck which usually possessed higher contamination than other associated species are shown in Table VIII. This species feeds almost exclusively on aquatic insect larvae and other invertebrates from the river bottom of the main river channel. The radioisotopic content of the various tissues are generally comparable to those of fish which consume similar food organisms with the exception of the proportionally much higher concentration of P^{32} in flesh of the ducks. The samples of duck flesh reported were pectoral muscles which contain a high concentration and a high turnover rate of phosphorus. The abundance of phosphorus is associated with the large energy requirements of these muscles that provide the muscular work for flight. Hanson and Kornberg[6] reported that the greatest concentrations of P^{32} in juvenile waterfowl

[a] Suckers, Catostomus macrocheilus Girard, collected at Dot Island Station, August, 1957.
[b] Bone and scales only tissue analyzed for Sr^{89-90}.

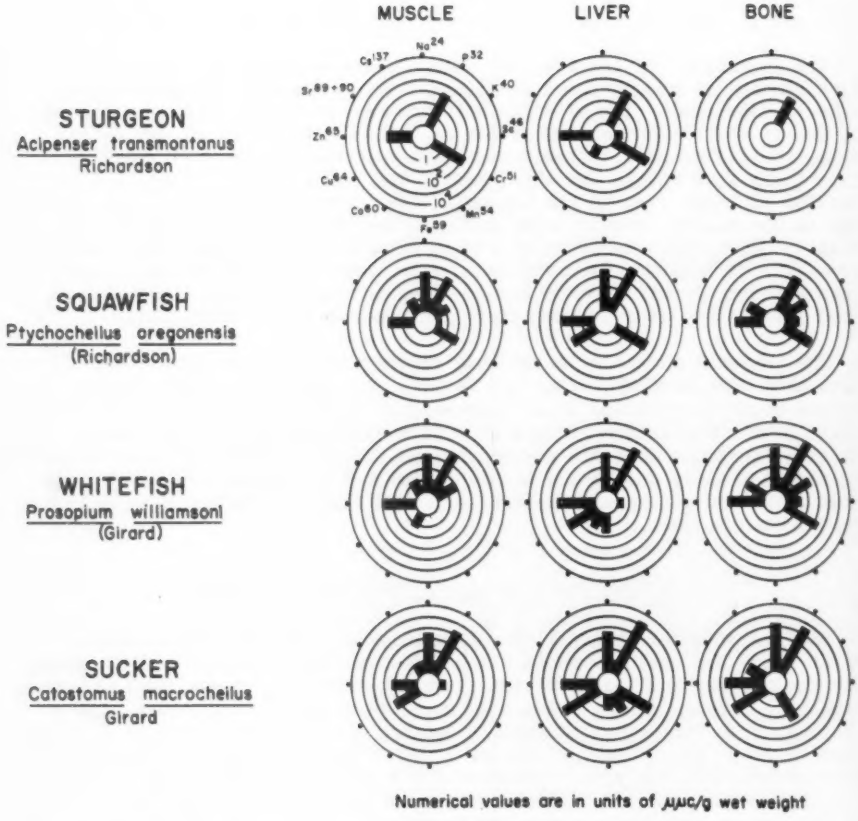

FIGURE 1. RADIOISOTOPES IN DIFFERENT KINDS OF FISH FROM THE COLUMBIA RIVER.

Table VIII. Radioisotopes in Tissues of Ducks[a]

Tissue	uc/g wet weight			
	Na^{24}	P^{32}	Sc^{46}	Cr^{51}
Bone	3.74×10^{-5}	1.36×10^{-2}		
Pancreas	1.03×10^{-4}	7.27×10^{-3}		
Liver	4.19×10^{-5}	7.20×10^{-3}	2.18×10^{-6}	
Spleen		6.32×10^{-3}		
Testes		5.46×10^{-3}		
Flesh	2.31×10^{-5}	4.41×10^{-3}		
Kidney	8.44×10^{-5}	3.80×10^{-3}	1.03×10^{-6}	
Heart	7.01×10^{-5}	2.97×10^{-3}		
Gut		2.56×10^{-3}	1.25×10^{-6}	1.85×10^{-4}
Lungs		2.28×10^{-3}		3.00×10^{-5}
Blood	2.51×10^{-5}	1.74×10^{-3}	1.01×10^{-6}	5.39×10^{-5}
Fat		9.28×10^{-4}		
Feathers		7.65×10^{-5}	4.47×10^{-6}	

	Co^{60}	Cu^{64}	Zn^{64}
Bone			
Pancreas	1.93×10^{-6}		5.16×10^{-4}
Liver	1.50×10^{-6}		5.63×10^{-4}
Spleen	1.87×10^{-6}		1.92×10^{-4}
Testes			1.70×10^{-4}
Flesh			6.84×10^{-5}
Kidney	1.69×10^{-6}	1.04×10^{-4}	1.90×10^{-4}
Heart	2.66×10^{-7}		1.32×10^{-4}
Gut	2.82×10^{-6}	2.01×10^{-4}	1.20×10^{-4}
Lungs	1.27×10^{-6}	8.06×10^{-5}	7.43×10^{-5}
Blood	1.61×10^{-6}	3.94×10^{-5}	4.17×10^{-5}
Fat			2.83×10^{-5}
Feathers			

[a]Barrow Goldeneye, Bucephala islandica (Gmelin). Collected at Dot Island Station, November, 1957.

occurred in the pancreas and skeleton but that in adult birds comparable concentrations occured in the muscle. The flesh sampled for these studies was also pectoral muscle. Leg muscle of ducks contained about 67 percent as much P^{32} as the pectoral muscles. The reason for the comparatively lower concentration of Zn^{65} in the iris and retina of ducks than in fish is unknown. The relatively high concentration of radiophosphorus in the pancreas is comparable to the amounts in pyloric caeca which contain functionally similar tissue in the fish.

CONCLUSIONS

Of the many radioisotopes that have been measured in Columbia River water, none were present in quantities near the recommended maximum limits for drinking water by the International Commission on Radiological Protection. Studies in which rats were maintained on reactor effluent that contained concentrations of radioisotopes several thousand times the concentrations in the river water indicated that the danger of assimilating harmful levels of radioisotopes by drinking Columbia River water was negligible. Significant quantities of various isotopes were concentrated, however, in the bodies of most organisms which had access to the contaminants via the natural food web. It is apparent that food organisms of man could accumulate hazardous levels of certain radioisotopes from water which contained concentrations of the contaminants that were well within the permissible limits for drinking water. Representative organisms are routinely sampled from natural environments which are exposed to dilution of effluent from the Hanford reactors to ascertain that the amounts of radioactive contamination are well below hazardous levels.

The data presented emphasizes the value of the need for radioecological research to further elucidate and evaluate environmental relationships that pertain to radioactive waste disposal.

REFERENCES

1. Perkins, R. W., Gamma-ray Spectrometric Systems of Analysis. Paper to be published.

2. Rediske, J. H. and A. A. Selders, The Absorption and Translocation of Strontium by Plants, Plant Physiol. 28:594-605, (1953).

3. Foster, R. F. and J. J. Davis, The Accumulation of Radioactive Substances in Aquatic Forms, Peaceful Uses of Atomic Energy, Proc. International Conf. in Geneva, August 1955, 13: 364-367, United Nations, New York, (1956).

4. Davis, J. J. and R. F. Foster, Bioaccumulation of Radioisotopes through Aquatic Food Chains, Ecology, in press, (1958).

5. Leiner, M., Zinc Content of Eyes of Bony Fishes. Klin. Wochschr. 22:130-1, (1943).

6. Hanson, W. C. and H. A. Kornberg, Radioactivity in Terrestrial Animals Near an Atomic Energy Site, Peaceful Uses of Atomic Energy, Proc. International Conf. in Geneva, August 1955, 13:385-388, (1956) United Nations, New York.

Representative HOLIFIELD. Mr. Theis will now give us some testimony on ground disposal.

TESTIMONY OF C. V. THEIS,[8] U.S. GEOLOGICAL SURVEY

Mr. THEIS. Mr. Chairman, members of the committee, the disposal of low-level waste to the ground has the advantages (1) that the waste moves very slowly compared to its movement in a surface stream and (2) that most of the radioactive elements are retained or delayed still further in their movement because of ion exchange with the rock materials through which they move.

These advantages are so great that medium-level waste may also be put in the ground in the proper environment under the proper control. The disadvantages of ground disposal are that it is difficult to determine exactly where the waste is and how fast it is moving and that the land used is permanently denied to further productive use.

Radioactive liquid waste put on the ground first percolates downward through sand or silt or whatever rock material is present to the water table. The pores of the material above the water table are ordinarily filled largely with air but below it the pores are completely filled with water.

After reaching the water table the waste moves with the ground water to a creek or river or other surface body of water at a lower altitude.

This paper will try to follow this movement, indicating what is known about it and what needs to be found out, both from the standpoint of fundamental studies and from that of local geology and hydrology.

GENERAL CHARACTERISTICS OF GROUND-WATER MOVEMENT

Many of the basic problems of the disposal of waste underground are the same as those involved in the production of water from wells. The disposal of waste at the surface and its percolation downward is a form of recharge to an aquifer, which has long been a study of hydrologists.

Injection into wells is the converse of production of water from wells.

Representative HOLIFIELD. Will you pause at that point and define what you mean by "aquifer" so the record will show it?

Mr. THEIS. I will try to use the words "water-bearing formation," from now on.

Representative HOLIFIELD. All right.

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[8] Born: Newport, Ky., March 27, 1900.
Education: Public Schools, Newport, Ky.; University of Cincinnati, C.E., 1922; University of Cincinnati, Ph. D. (geology), 1929.
Work history: Instructor, University of Cincinnati, 1922–29. Geologist, Kentucky Geological Survey, summers 1922–26, 1928. Junior geologist, U.S. Corps of Engineers, Cincinnati, Ohio, 1929–30. Associate to principal geologist, U.S. Geological Survey: Work in ground-water geology and hydrology in Tennessee, New Mexico, and Texas, 1930–36; district geologist, ground-water branch, Albuquerque, N. Mex., 1936–51 (assignments in interim to military geology, to water-supply and permafrost studies on Alaska Highway, and to studies of mining hydrology in Michigan); coordinator, water-supply and waste-disposal studies of U.S. Geological Survey for U.S. Atomic Energy Commission, 1951–1957; research scientist, presently on waste-disposal studies, 1957 to present.

Mr. THEIS. The body of knowledge that has been gained in studies of water supplies for industrial, irrigation, and municipal use is, therefore, the point of departure for studies of waste disposal to the ground.

A study of the geology indicates what aquifers are available and their continuity. Laboratory tests and pumping tests determine the permeability of the material, expressed, among other ways, as the quantity of water in gallons transmitted per day through each square foot of cross section of the material under a hypothetical slope of water level of 1 foot per foot.

This describes how easily the water moves through the formation.

This, together with measurements of water levels in wells to give the actual slope of the water table, gives the average quantity of water moving per square foot of cross section of the aquifer and the approximate direction in which it is moving.

By pumping tests and laboratory tests the amount of pore space in the material can be ascertained. With this and the quantity of water flowing, the average velocity can be computed.

We can, therefore, estimate the average width that a band of contaminant would occupy, the average rate at which the waste would travel, about where it would come to the surface, and the approximate path it would take to get there.

SKETCH OF HYDROLOGY AT WASTE-PRODUCING SITES

It may be pertinent to consider very briefly the geology and hydrology of the present main waste-producing sites to show how diverse are the conditions for waste disposal at these sites and, by inference, at other sites to be used in the future.

The accompanying table summarizes the main hydrological factors affecting the movement of waste from these sites, as determined by work of the Geological Survey in collaboration with the local staffs at Hanford and Oak Ridge.

(The table referred to follows:)

Diversity of hydrological conditions at present waste-producing sites

	Hanford	Reactor Testing Station, Idaho	Oak Ridge	Savannah River
Main formations involved in waste disposal	(a) Gravel and sand (glacio-fluviatile formation); (b) gravel, sand, and silt (Ringold formation).	Basalt	Shale (Conasauga formation).	(a) Fine sand and silt (formations of Tertiary age); (b) gravel and sand (Tuscaloosa formation).
Depth to water table (feet)	About 200	About 200 to 600	About 20	About 20.
Permeable sediments above water table (feet)	do	About 0–60 (alluvial sediment overlying basalt).	do	Do.
Permeability (gallons per day per square foot)	(a) 10,000 to 60,000; (b) about 400.	Erratic; about 10,000 to 20,000?	Low; 1 to 10	(a) 1 to 100 in various beds; (b) about 1,000.
Average rate of travel (feet per day)	(a) 15; (b) about 1	20?	About 1	About 1.
Place of emergence at surface	Columbia River	Snake River	Small creeks, thence to Clinch River.	(a) Small creeks, thence to Savannah River; (b) Savannah River.
Distance to point of emergence	About 10 miles	About 100 miles	About 400 feet	(a) About 500 feet; (b) a few miles.

Mr. THEIS. At Hanford some 200 feet of very permeable sand and gravel of glacial origin immediately underlie the waste disposal site (glaciofluviatile deposits).

Below this is another earlier glacial formation (Ringold formation) about 800 feet thick, consisting largely of silt and fine sand but containing a gravel and sand lens about 150 feet thick.

The gravel and sand of the Ringold are much less permeable than the overlying material. The water table lies largely within this formation but extends in some places at the waste disposal site into the overlying more permeable deposits.

Below all this is basalt, extending below a depth 10,000 feet in a nearby oil test. The permeability of the upper deposits has in places a nearly fantastic value of 60,000 gal/day/ft.^{2}; that of the Ringold gravels about 400 gal/day/ft.^{2}; and of the basalt much less.

The average rate of travel of the water in the upper deposits is around 15 feet per day, and in the Ringold, a fraction of a foot per day. The fastest rate of movement may be several or even many times the average rate. The water moves to the Columbia River about 10 miles away.

Because of the combination of arid climate, permeable surficial deposits, and deep water table at Hanford, most of the radioactivity of the intermediate-level wastes is trapped by ion exchange in the sediments as the waste percolates downward to the water table.

At the reactor testing station in Idaho, near the chemical processing plant, the water table lies about 450 feet below the surface in a basalt that is remarkably permeable, having a coefficient of 10,000 to 20,000 gal/day/ft.^{2}.

Overlying the basalt in some places are gravel and sand and some silty and clayey lake beds, up to about 150 feet thick. Movement of water in the basalt is erratic because the water moves through certain beds and probably in places through open tubes in the old basaltic lava, and at an average rate, we think—determination of such quantities in basalt and limestone is difficult—of about 20 feet per day.

I believe I heard testimony of 35 feet per day. It doesn't make much difference.

The ground water and the wastes discharge into the Snake River about 100 miles away, in the noted Thousand Springs area.

At Oak Ridge all the rocks are tilted to the southeast at about 30 degrees. The formation of interest to waste disposal is the Conasauga shale, about 1,000 feet thick, in which the waste disposal pits are located. The Conasauga is underlain by a rather dense sandstone (Rome sandstone) having about the same thickness, and is overlain by the Knox dolomite, about 1,500 thick.

But both of these formations are ridge formers and topographically unsuited for waste disposal. The permeability of the Conasauga shale itself is less than 1 gal/day/ft.^{2}, but water and waste move through various fractures and bedding planes also, and they discharge into small streams a few hundred feet from the pits. The natural water table is about 20 feet below the land surface pits.

At the Savannah River plant there are about 400 feet of fine sand and silt beds of Tertiary age, underlain by about 300 feet of coarser sand and gravel called the Tuscaloosa formation, of Cretaceous age.

Below this is the granitic basement. The Tertiary fine sand and silt have low but variable permeabilities; the Tuscaloosa formation is a very good aquifer and furnishes water to nearby towns. The water table is from 0 to 30 or 40 feet below the surface.

Waste introduced at the surface moves to small adjoining creeks a few hundred yards away, probably at a rate of less than a foot per day, and thence to the Savannah River. A waste liquid appreciably denser than water could move into the Tucaloosa formation, where it probably would move at a rate of about 1 foot per day toward the Savannah River a few miles away or perhaps to the sea about 75 miles away, depending upon the location of the waste-disposal site within the reseveration.

These sketches of the geology at these four sites indicate the diversity of rates of movement, character of earth materials involved, and distances to points of emergence at the surface.

The diversity is much greater than can be represented here. Each prospective waste-disposal site represents an almost new specific problem, and the local geology and hydrology must be known in greater detail than is necessary for almost any other use of the resources of the terrain.

ADDITIONAL GEOLOGICAL AND HYDROLOGICAL INFORMATION NEEDED IN WASTE-DISPOSAL STUDIES

The techniques of ground-water studies used for estimating ground water reserves give average values—average velocity and average path of flow. In radioactive waste disposal the average is necessary but not good enough.

All deposits of sand and gravel are, in varying degree, lenticular—coarse beds and lenses are interbedded with fine beds and lenses; in the coarse materials waste moves more rapidly than the average rate, in the fine materials, more slowly.

Other geologic materials have the same characteristic of variability. In addition, if the lenses are elongated in one direction, or the strata are inclined steeply, or in many other geologic situations, an additional complication arises.

The direction of ground water movement is generally inferred from water levels in wells, the water tending to move in the direction in which the slope or gradient of water levels is steepest.

However, if there is one direction in which water moves more easily than in another, the direction of flow inclines in this direction. Hence, these factors of heterogeneity and anisotropy assume great importance in waste disposal.

The Geological Survey and the local staffs at Hanford and Oak Ridge are studying this problem. The important effects of irregularities in the rock units upon the path of waste requires that the geology be learned in great detail at each site and many wells must be drilled to get these details.

ION-EXCHANGE PHENOMENA

One of the characteristics of the ground that is most important in radioactive-waste disposal is its ion-exchange capacity. When a solution containing unusual elements—the radioactive elements in the

present case—passes through earth materials, the new elements are exchanged to some extent with common elements, usually sodium and calcium, which are already present in the soil.

This is the same process that occurs in a home water softener, where the calcium in the water is exchanged for sodium. Ion exchange is accomplished by clay and silt minerals in the soil, which are generally present in some amounts even in sandy and gravelly material.

Tests made in the laboratories of the Geological Survey have shown that the near-surface earth materials from Atomic Energy Commission sites have exchange capacities ranging from one-fourth to 15 equivalents per cubic foot (one-half to 30 milliequivalents per 100 grams), or in other words, each cubic foot contains from 5 to 300 grams of exchangeable sodium and calcium.

Even the smaller quantities are immense compared to the chemical quantities of radioactive ions that are likely to be put in the ground and are large compared to the amount of inert elements in the waste which accompany and interfere with the adsorption of the radioactive elements.

The amount of ion exchange varies not only with the character of the waste but also with the type of clay mineral present. The Geological Survey is making studies of ion exchange minerals and the Hanford studies are described in the Hanford paper that has been submitted to you.

In general, also, waste moves underground in such a way that the opportunity for ion exchange is minimized. In sandy materials the waste and the natural ground water move at the greatest rate through the coarser lenses of material, in which the ion exchange is least; and in shaly material, such as those at Oak Ridge, the waste moves largely through fractures and bedding planes and leaves the ion-exchange capacity of most of the shale untouched.

Certain isotopes, notably ruthenium-106, are but little affected by ion exchange, and deleterious inert components of waste, such as nitrates and fluorides, are not affected at all.

BASIC HYDROLOGIC STUDIES NEEDED

A waste contained in a stream of ground water moving through a sandy deposit disperses both along and transverse to the direction of flow. Dispersal in the direction of flow reduces the concentration of the contaminant if the waste is a "slug" temporarily introduced and gives a warning at a locality downstream of the approach of a continuously introduced waste stream.

Dispersal across the direction of flow spreads a contaminant more widely but reduces the concentration. Because our knowledge of the processes of dispersion is incomplete, this phenomenon must be investigated in the laboratory and to the extent possible in the field.

Excellent laboratory and theoretical work has been done on this problem, particularly longitudinal dispersion, at Harvard and at the University of California and elsewhere.

The Geological Survey is working on transverse dispersion at Columbia University. The effects in any laboratory experiments are important because of the scale.

Because the effects of this type of dispersion, dependent upon variability of pores in a uniform sand, vary only with the square root of the distance traveled, the effects over field distances of a mile or more are much less important.

However, the effective dispersion in the field is probably larger than that indicated by laboratory experiments because of the variability in permeability of the different beds and lenses discussed previously. Dispersion in the field is being studied at Hanford by the Hanford staff and at the National Reactor Testing Station by the AEC and the Geological Survey.

Another field in which knowledge is incomplete is that of movement downward through porous materials to the water table, as under the cribs disposing waste at Hanford, and of lesser importance at other atomic energy installations in the arid West.

Water so moving is acted upon by capillary forces so that the column of water leaving a crib or other point of supply at the surface is pulled out laterally, as in a wick, to occupy a cross section of larger area than that of the crib above.

This expansion increases the volume of material available for ion exchange. However, many details of this downward migration are poorly understood. Much exploration of the shape of the wetted column has been done at Hanford.

Laboratory and theoretical work is being done by the Geological Survey. It may be expected that better knowledge will lead to better and safer use of the ground for this type of disposal.

Several types of studies by the Geological Survey and others, not directly related primarily to the waste-disposal problem, nevertheless have a bearing on it. The Survey is developing an analog computer for the solution of complicated problems in ground-water movements which will probably find application in all areas of waste disposal.

It is helping to develop instruments for the better exploration of wells and the determination of radioisotopes in waste-disposal areas. It has begun tritium studies, which will help to trace the movement of water under natural conditions; the knowledge gained will have bearing on waste movement underground.

Area studies of ground water throughout the United States by the Geological Survey, State agencies, and others will contribute more general knowledge of characteristics of water movement, and may have ready specific knowledge when new sites for waste disposal must be selected.

SUMMARY

In summary, the safe and efficient disposition of waste to the ground demands, first, and of paramount importance, an exploration of the geology and hydrology of waste-disposing sites much more thorough—and expensive—than is usually considered necessary for the location of industrial plants.

Secondly, a considerable expansion of our basic knowledge of movement of ground water and the geochemistry involved; and, thirdly, a followup monitoring program at any waste-disposing site to insure that the geology and hydrology have been properly interpreted.

That concludes my statement, Mr. Chairman.

Representative HOLIFIELD. Thank you very much.

Are there any questions from the committee and the staff?

Chairman DURHAM. What you are telling us, Doctor, is that we have to be careful in selecting places where we are going to make the disposal?

Mr. THEIS. That is correct.

Chairman DURHAM. I notice most of your comment has been on the composition of the earth at less than a thousand feet from the surface. We have pretty complete logs of different kinds of geological formations down to as low as 10,000 or 12,000 feet. Do you have any comment to make on the problem of underground water stream contamination which will eventually come to the surface at lower levels?

Mr. THEIS. Of course this discussion has been on low and intermediate level wastes.

Chairman DURHAM. I am thinking now of using a deeper level for the storage of high-level waste.

Mr. THEIS. The low-level wastes particularly are in large volume. The permeability of these rocks are much greater in general than the permeability of deeper lying rocks. There are places where large quantities of water and waste could be put into deeper formations but in general they are much less permeable. The oil geologist measures his permeability in millidarcies, thousandths of a darcy. These values that I have been speaking of here come up in the range, in the case of Hanford, of 3,000 darcies. The rocks are much more permeable near the surface. That is the reason I think that the wastes that are produced in bulk, the low-level waste, will be put in near the surface. The question of the deeper formations comes in with respect to their use for putting in high-level waste. I believe these small-volume wastes could be put into carefully chosen deep formations through carefully constructed wells without contaminating any water supplies.

Representative HOLIFIELD. Mr. Toll.

Mr. TOLL. Dr. Theis, could you give a very rough estimate as to the number of gallons at Hanford, for example, of these types of low-level wastes that are disposed directly into the ground as compared with the number of high-level wastes that are contained in storage tanks, say in a month or a year's operation? Whatever time limit you wish to use.

Mr. THEIS. I think the data given, I believe by Dr. Parker, show that there is something like 52 million gallons of high-level waste in tanks but that Hanford has put into the ground in the last 2½ or 3 years 30 billion gallons of very low-level waste and something like 3 billion gallons of intermediate level waste.

Mr. TOLL. That would be roughly 600 times as much.

Mr. THEIS. Something like that.

Representative HOLIFIELD. Thank you, Mr. Theis.

We have some additional papers on "Disposal of Low and Intermediate Level Radioactive Wastes to the Ground" to go in the record at this point.

(The material referred to follows:)

DISPOSAL OF RADIOACTIVE LIQUID WASTES TO THE GROUND AT HANFORD.

This paper was prepared by D. W. Pearce of the Hanford Laboratories, Hanford Atomic Products Operation, General Electric Company and filed for the record of those hearings upon the request of the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy.

Low level liquid waste disposal to the ground at Hanford has been supported between a closely correlated and balanced program of theoretical study, laboratory and field experiment, and observational experience (1, 2, 3, 4). Extensive effort in geology and hydrology, mineralogy and soil chemistry, analytical chemistry and engineering has been applied to ground disposal problems. It is the purpose of this presentation to outline the more important findings from the research and development in each of these areas, to show how this has pointed the way for plant practice, and to indicate in general the future course of the work.

Geology and Hydrology

The U. S. Geological Survey has studied the general geology of the Hanford Works. The work of the Hanford geologists has been the refining and detailing of this. The area (Figure 1) is underlain by the Columbia River basalts, a series of very hard, dense lava flow rocks up to more than 10,000 feet thick (Figure 2). These have been folded into structures with a general trend varying from W-E to NW-SE (Figure 3). The surface expressions of most significance locally are the anticlinal or upfolded ridges: Rattlesnake Hills at the southwestern boundary, the Gable Mountain-Gable Butte alignment on the site, and the Saddle Mountains at the northern boundary (Figure 1). Synclines or down folds between the anticlines extend to 700 feet below the ground surface. Overlying the synclines in the basalts are thick covers of lake- and stream-deposited semi-consolidated sands, gravels, silts and clays of the Ringold Formation. Over this are wind blown silts and sands of the Palouse Formation; the glacial- and river-deposited gravels and sands

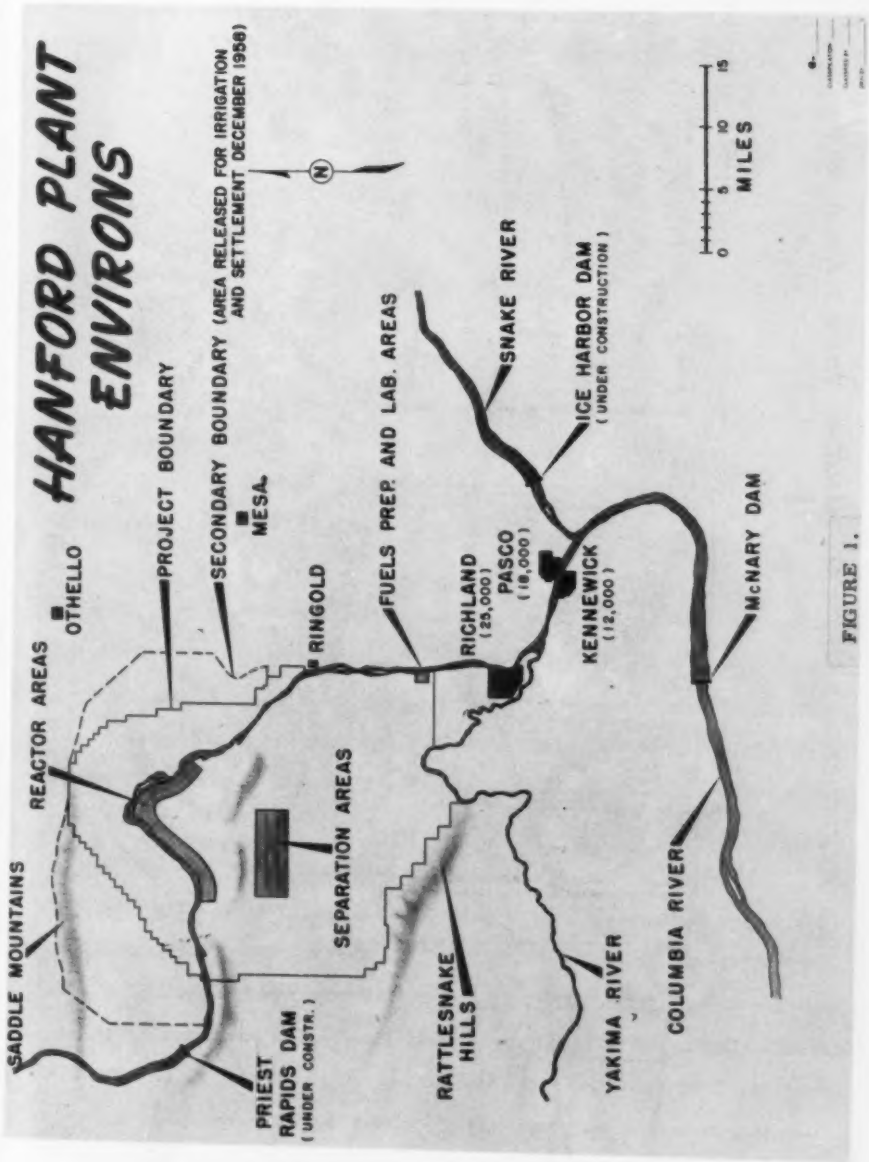

HANFORD PLANT
ENVIRONS
SADDLE MOUNTAINS
REACTOR AREAS
OTHELLO
PROJECT BOUNDARY
SECONDARY BOUNDARY (AREA RELEASED FOR IRRIGATION AND SETTLEMENT DECEMBER 1958)
MESA
RINGOLD
FUELS PREP. AND LAB. AREAS
SEPARATION AREAS
PRIEST RAPIDS DAM (UNDER CONSTR.)
RATTLESNAKE HILLS
RICHLAND (25,000)
PASCO (18,000)
KENNEWICK (12,000)
SNAKE RIVER
ICE HARBOR DAM (UNDER CONSTRUCTION)
McNARY DAM
YAKIMA RIVER
COLUMBIA RIVER
N
0 5 10 15
MILES

FIGURE 1.

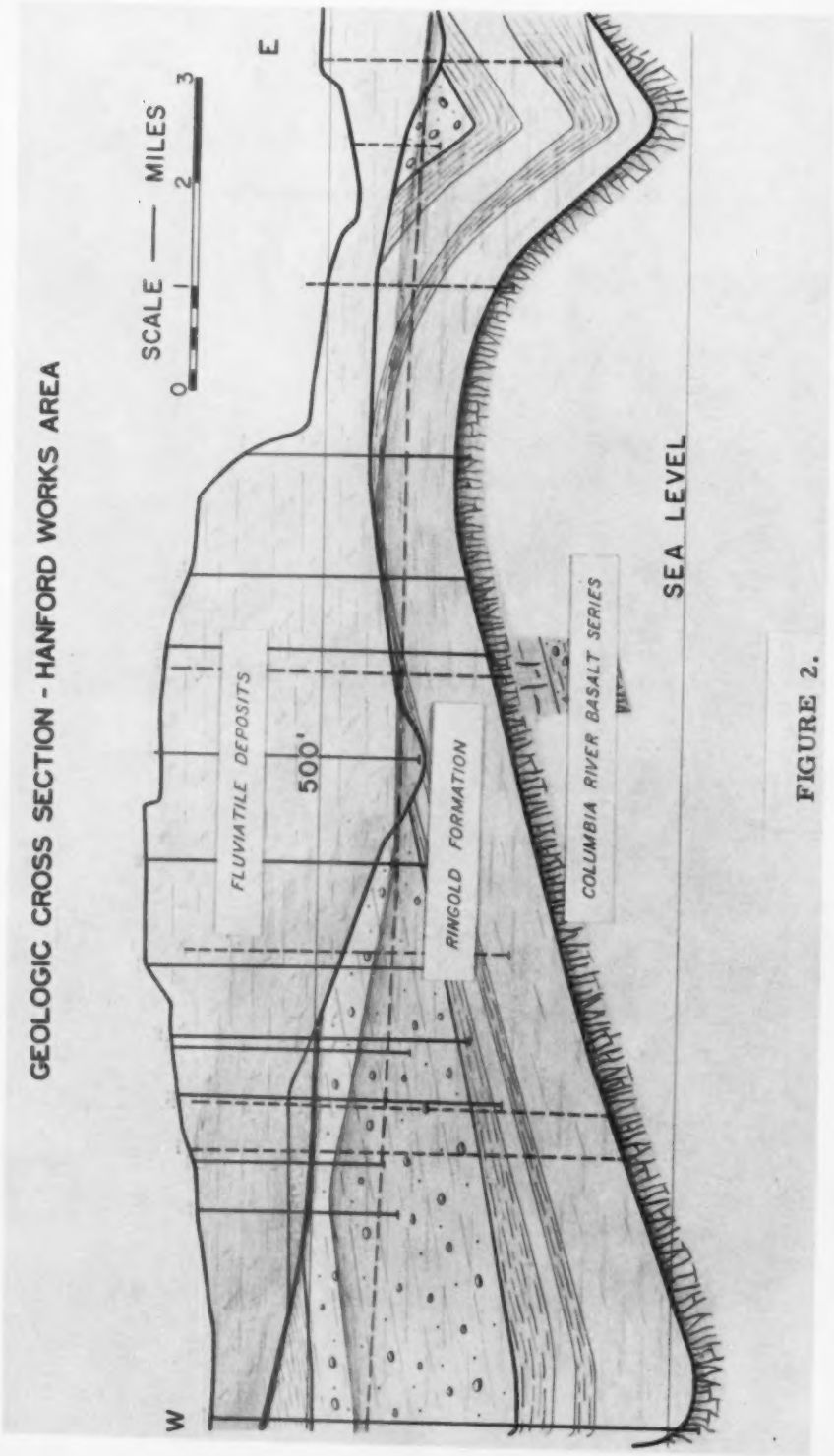

GEOLOGIC CROSS SECTION - HANFORD WORKS AREA
SCALE — MILES
0
1
2
3
W
E
FLUVIATILE DEPOSITS
500'
RINGOLD FORMATION
COLUMBIA RIVER BASALT SERIES
SEA LEVEL

FIGURE 2.

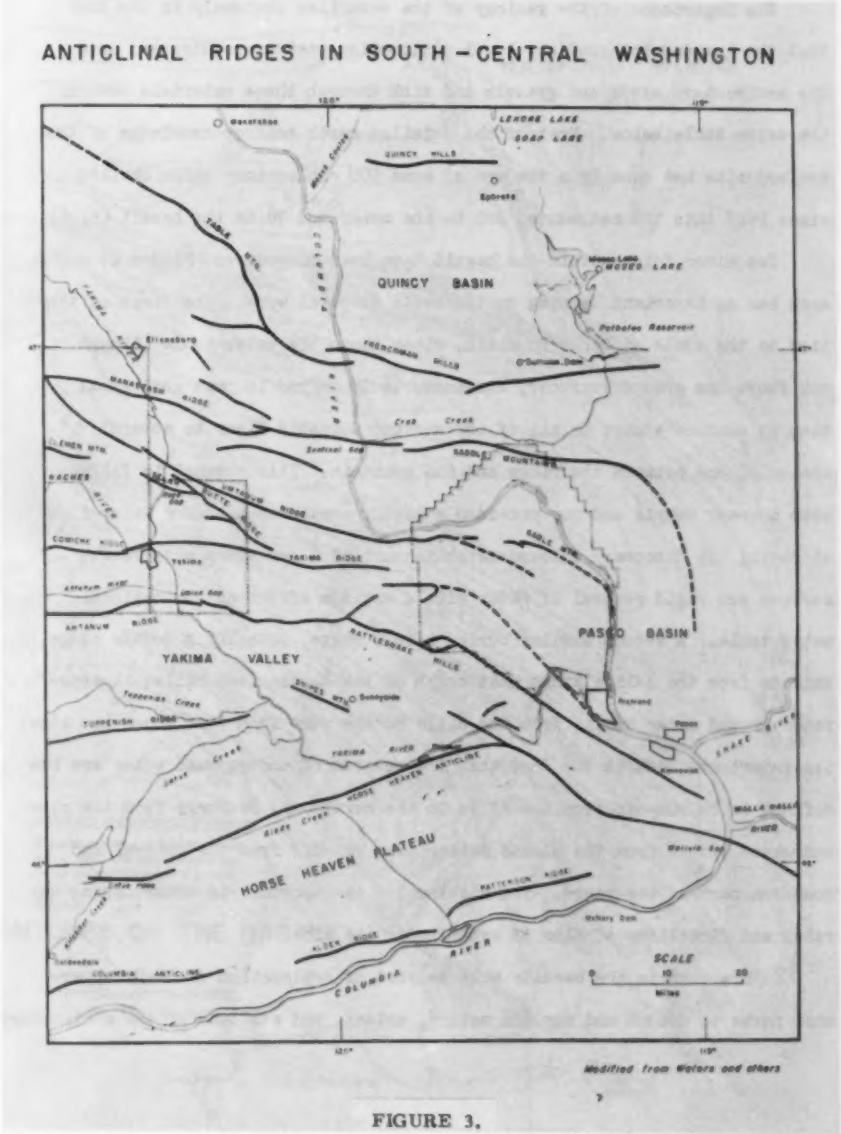

ANTICLINAL RIDGES IN SOUTH-CENTRAL WASHINGTON
QUINCY BASIN
PASCO BASIN
YAKIMA VALLEY
HORSE HEAVEN PLATEAU
COLUMBIA RIVER
SCALE
Modified from Waters and others

FIGURE 3.

of the Touchet Formation, and equivalent deposits; and at the surface terrace gravels, wind-blown and reworked materials.

The importance of the geology of the area lies obviously in the fact that the low and intermediate level radioactive wastes are disposed into the sedimentary sands and gravels and sink through these materials toward the water table below. Most of the detailed earth science knowledge of the Hanford site has come from the use of some 500 exploratory wells drilled since 1947 into the sediments, 320 to the water and 76 to the basalt (5, 6).

Two minor folds within the basalt have been discovered (Figure 4) and each has an important bearing on the waste disposal work. The first of these lies to the south of Gable Mountain, rises above the water table (though not above the ground surface), and undoubtedly served in past geological time to confine a part or all of the ancient Columbia River to several channels, one between the ridge and the mountain. This channel is filled with coarser debris and now provides a highly permeable path for water flow at depth; the discovery allowed establishment of a new swamp site at the surface and rapid removal of water with a minimum effect on the regional water table. A second similar buried basalt ridge, actually a double ridge, extends from the Yakima Ridge just north of the Rattlesnake Hills; it separates ground water coming from the hills to the west from that under the site; its importance lies in the fact that the sources of underground water are now defined to be run-off from the hills to the northwest, recharge from the river, and waste waters from the plants rather than run-off from the central and southern part of the range. The distinction is important in establishing the rates and directions of flow of water under the site.

Future work in the basalts will consist of exploration of their uppermost parts to detect and map the nature, extent, and attitude of the sedimentary

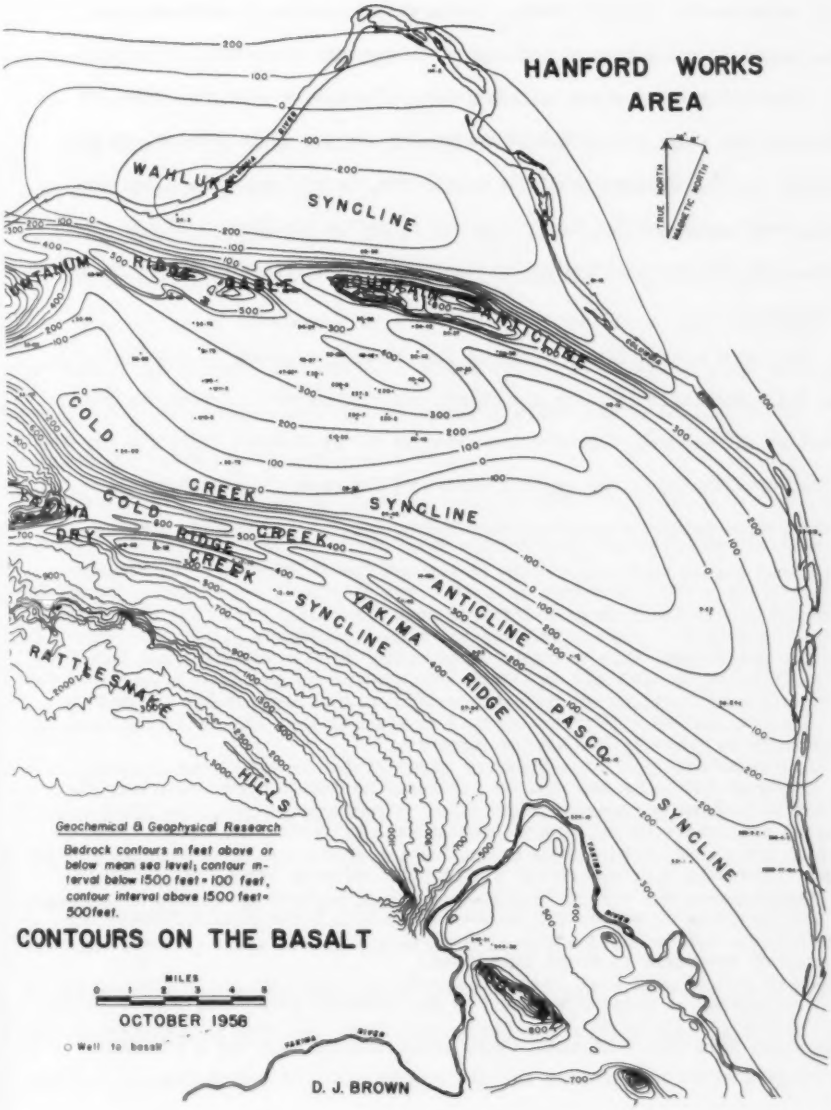

HANFORD WORKS
AREA
TRUE NORTH
MAGNETIC NORTH
WAHLUKE
SYNCLINE
RIDGE
SYNCLINE
COLD
CREEK
SYNCLINE
COLD
CREEK
RIDGE
CREEK
SYNCLINE
ANTICLINE
YAKIMA
RIDGE
PASCO
SYNCLINE
RATTLESNAKE
HILLS
Geochemical & Geophysical Research
Bedrock contours in feet above or below mean sea level; contour interval below 1500 feet = 100 feet, contour interval above 1500 feet = 500 feet.
CONTOURS ON THE BASALT
MILES
0 1 2 3 4 5
OCTOBER 1956
Well to basalt
D. J. BROWN

FIGURE 4.

and fragmental interbeds which are present there. This will be done largely through the use of exploratory wells probing the structure at selected points. Such deeper wells, combined with structural information at hand and from other wells in the region should aid in determining the shape of the basin and the feasibility of disposal to these beds. Plans have also been made for more detailed study of the basalt surface by the use of geophysical seismic methods (5, 7). Such mapping will supplement the well network, allow the more advantageous positioning of new wells, define the closure of the synclines, and aid in determining the feasibility of disposal within or below the basalt.

The subdivision of the lowermost post-basalt sediments at the Hanford site has been difficult since the formations of greatest interest are poorly or not at all exposed. Careful measurements in the Ringold Formation exposed in the White Bluffs on the eastern border of the area (8) and observation of the ground water through long-term hydrographic measurements, pumping tests, and tracer tests all served to support the finding that the Ringold Formation was at least in part deformed with the basalt (9). The soil science work has reinforced this concept. Recognition of the situation has permitted improved location of disposal facilities and more precise prediction of paths to be taken by the wastes disposed.

Study of the sediments will be continued to define more completely their chemical and mineralogical composition as well as their structural relationships. This work will contribute strongly to defining areas most suitable for the reception of wastes and in predicting with increasing exactness the behavior of materials in these structures.

The volumes of water discharged by the chemical processing plants to the swamp sites have been mentioned. Such large volumes have had a profound

effect upon the regional water table and this has been studied in some detail through manual and automatic measurement in the well network. Figure 5 shows the contours on the water table interpreted from the earliest measurements and general hydrological knowledge. Similar maps have been prepared periodically over the years (10, 11) and with increasing accuracy as more wells became available for this use; the latest is shown in Figure 6. Water mounds have been created on the water table, their location, elevation, and shape depending upon the location of the swamp or swamps which fed them and upon the nature and geological attitude of the sedimentary formations in which they lay. It is of importance to study these mounds since they determine the direction and rate of flow (12) of the ground water and this in turn is important in the proper location of disposal sites and in following the underground movement of mobile materials.

The ability of local aquifers to transmit water is studied by means of well pumping tests or by other, more specialized, in-well measurements. The pumping tests (see Figure 7) are generally performed with a submersible, electric pump (13). The tests consist of pumping a well at a measured rate for a period of eight hours or more and observing the rate of recovery of the water level in the well as detected by an electric sounding tape (14). A single-well test such as this permits estimation of the "transmissibility" of the local aquifer, an expression involving the summed permeabilities of all the individual beds forming the saturated zone. From these data it is possible to obtain an average field permeability figure for the material tested. Pumping tests are also performed in wells located near a pattern of observation wells; in such cases it is additionally possible to determine the coefficient of storage. This characteristic defines the ability of the aquifer to store water and thus determines the quantity of water yielded by

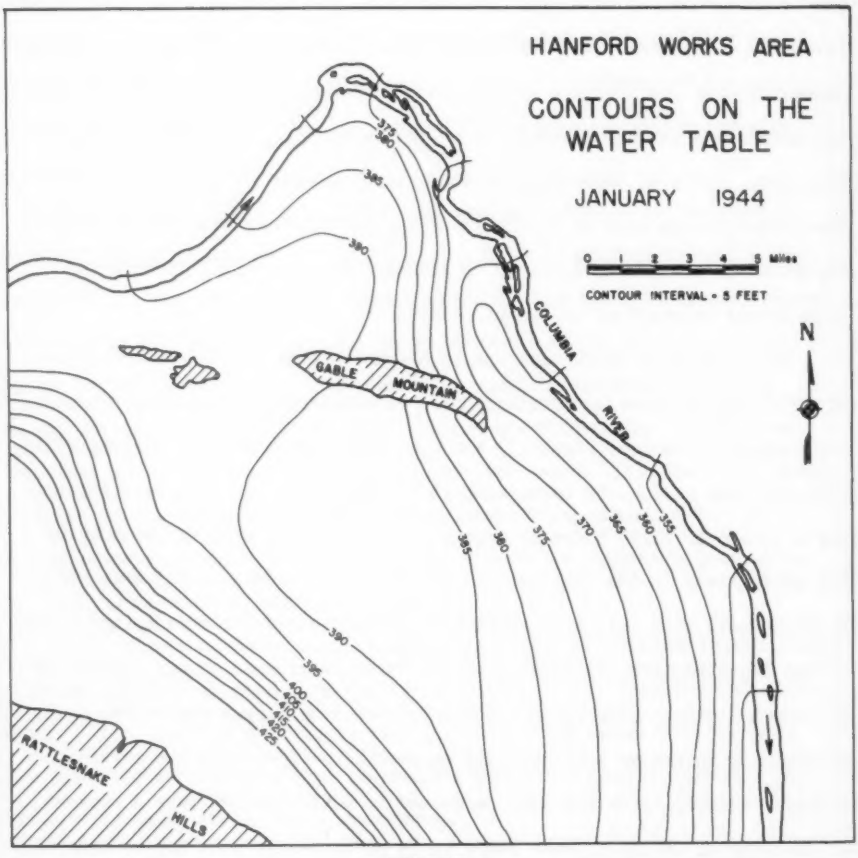

HANFORD WORKS AREA
CONTOURS ON THE WATER TABLE
JANUARY 1944
0 1 2 3 4 5 Miles
CONTOUR INTERVAL = 5 FEET
N
COLUMBIA RIVER
GABLE MOUNTAIN
RATTLESNAKE HILLS
375
380
385
390
395
400
405
410
415
420
425
370
365
360
355

FIGURE 5.

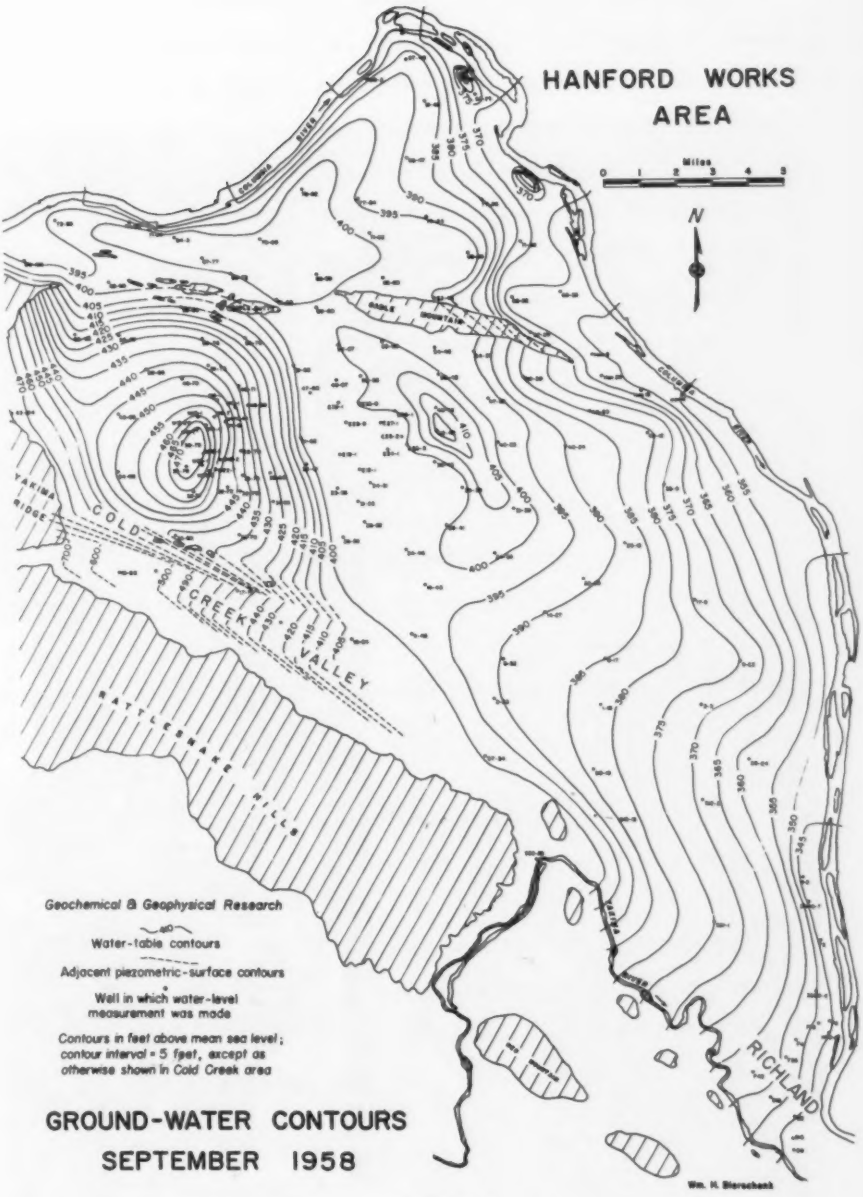

HANFORD WORKS AREA
Miles
0 1 2 3 4 5
N
COLUMBIA RIVER
YAKIMA RIDGE
COLD CREEK VALLEY
RATTLESNAKE HILLS
RICHLAND
Geochemical & Geophysical Research
Water-table contours
Adjacent piezometric-surface contours
Well in which water-level measurement was made
Contours in feet above mean sea level; contour interval = 5 feet, except as otherwise shown in Cold Creek area
GROUND-WATER CONTOURS
SEPTEMBER 1958
Wm. H. Bierschenk

FIGURE 6.

FIGURE 7.

gravity drainage. A number of single and multiple well pumping tests are performed at Hanford permitting permeability estimates for the principal geologic beds comprising the aquifer. These tests show that the permeability of the Ringold clays is about 10 gal/day/ft^2 while that of the Ringold silts, sands, and gravels is from 100 to 600 gal/day/ft^2. In sharp contrast, the permeability of the glaciofluviatile sands and gravels ranges from about 12,000 to 66,000 gal/day/ft^2. With such quantitative data, it is possible to predict the direction and to estimate the rates of movement of the ground water in the various aquifers. The directions of movement are also those which would be taken currently by a mobile radioisotope in the ground water while the rates of movement suggest the minimum amount of time available for radioactive decay.

Another technique is under study for determining permeabilities of soil in the immediate vicinity of a well. In this technique the well casing is sealed at two levels with inflatable rings making up part of a device termed a "packer". Water is pumped into the sealed off section at a fixed rate. The pressure required to pump water into the casing and out through the soil at this rate is measured and provides an index to the permeability. This index to permeability will be correlated to laboratory measurements of permeability of soil samples taken from the strata during the well-drilling operation. Such data should provide important confirmation of the field permeabilities from which the rate of ground water movement is estimated.

The local ground water movement ranges from immeasurably low rates up to hundreds of feet per day being determined by the permeability of the sediments through which the water moves and the hydraulic gradient furnishing impetus for the movement (15). The rate of movement, therefore, not only

differs markedly from point to point across the project, but also may be significantly different in various beds, giving rise to vertical variations. A technique was applied to the measurement of "point" velocities within the aquifer by means of dilution rate measurements within a well (11). The tests utilize a pair of electrodes and a conductivity bridge to measure the concentration of an electrolyte solution mixed with the water in the well (Figure 8). The density of the electrolyte is carefully adjusted to be very close to that of the water in the well to avoid problems resulting from sinking of a high density solution. The rate of dilution of the electrolyte is a function of the rate of movement of ground water through the well. The ground water velocity may be derived from the dilution rate data by applying the formula

$$V = \frac{\pi \frac{1}{2} G \ln \frac{C_o}{C}}{4ts}$$

where: V = velocity, ft/day

G = diameter of well, feet

C_o = initial concentration (at time 0)

C = final concentration (at time t)

t = time, days

s = fractional porosity of the soil.

The application of this technique is not without problems and further development will be directed toward improved reliability. Without granting undue significance to individual velocity determinations it is possible to use the technique to develop reasonable flow distribution data that are felt to be reliable.

Hanford soils located above the local water table are generally quite dry, a typical analysis showing on the order of 4% water by weight. This material

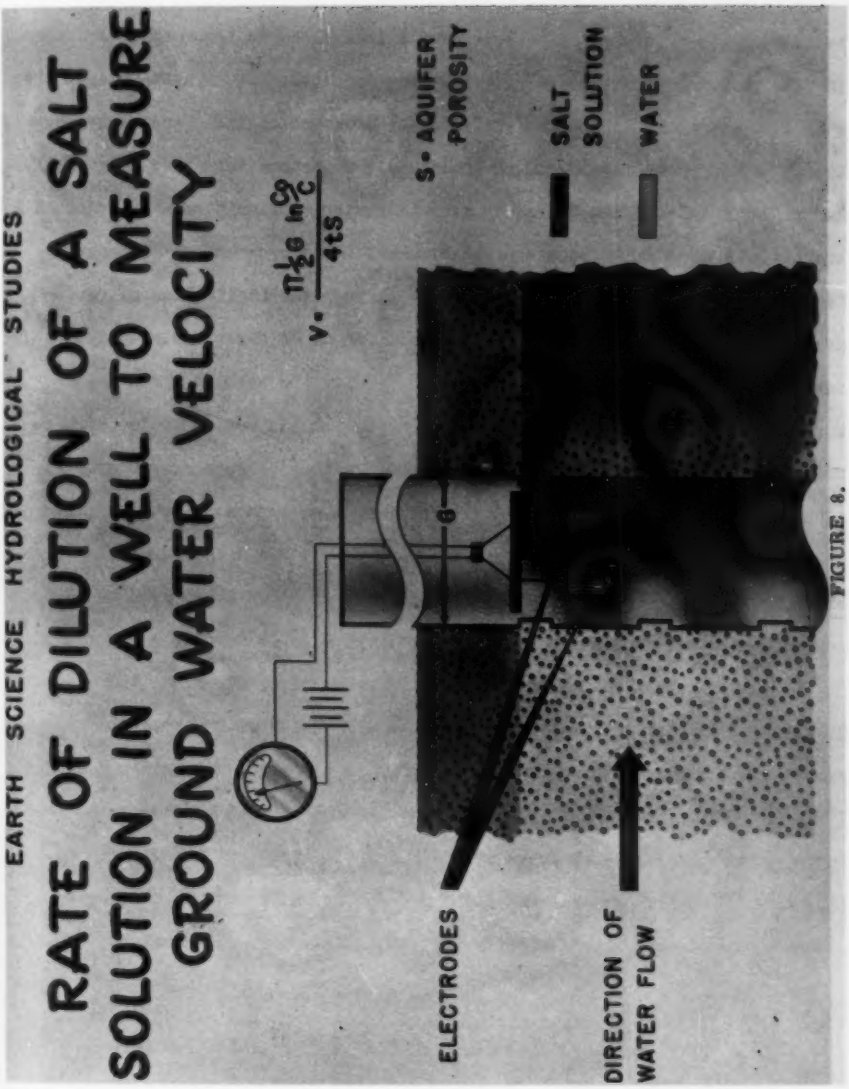

EARTH SCIENCE HYDROLOGICAL STUDIES
RATE OF DILUTION OF A SALT SOLUTION IN A WELL TO MEASURE GROUND WATER VELOCITY
$v = \frac{\pi \frac{1}{2}\theta \ln \frac{c_0}{c}}{4ts}$
S - AQUIFER POROSITY
SALT SOLUTION
WATER
ELECTRODES
DIRECTION OF WATER FLOW

FIGURE 8.

has a significant capacity for retaining additional liquids in the voids by capillary attraction. For some types of waste it has been found convenient to utilize this "blotter" effect to immobilize waste liquids without dependence on soil reactions to decontaminate them (16) (see Figure 9). In practice a conservative approach is applied to the utilization of this "specific retention" disposal technique because of the lack of basic information concerning the long term behavior of material thus retained. It is certain that the soil will gradually lose excess moisture by downward drainage and by evaporation. Research studies of the phenomenon are by nature very long range and laborious because of the extremely slow migration of liquid when only modest amounts of excess moisture are present. Work is in progress to study the feasibility of accelerating this research through the application of excess gravitational force in a centrifuge. Measurements of gravity-time-moisture retention relationships are being used to predict the rate of drainage of various beds of soil and to permit more exact calculations of the soil capacity to retain liquids. Data obtained from these centrifuge experiments together with measurements of the moisture of samples of the affected formations indicate that the materials into which wastes are disposed may be expected to have a specific retention capacity, as established by natural drainage over extended periods of time, of from 6 to 18 percent.

Specific retention disposal is used as a technique for expeditious disposal of smaller volumes of waste that are marginal with respect to ion exchange with soils because of their chemical nature or large salt content. It is not applicable to wastes with activities drastically greater than those acceptable for usual large volume ground disposal practice.

Another instrument has been developed and is under test to measure ground water direction and velocity of flow. The instrument consists

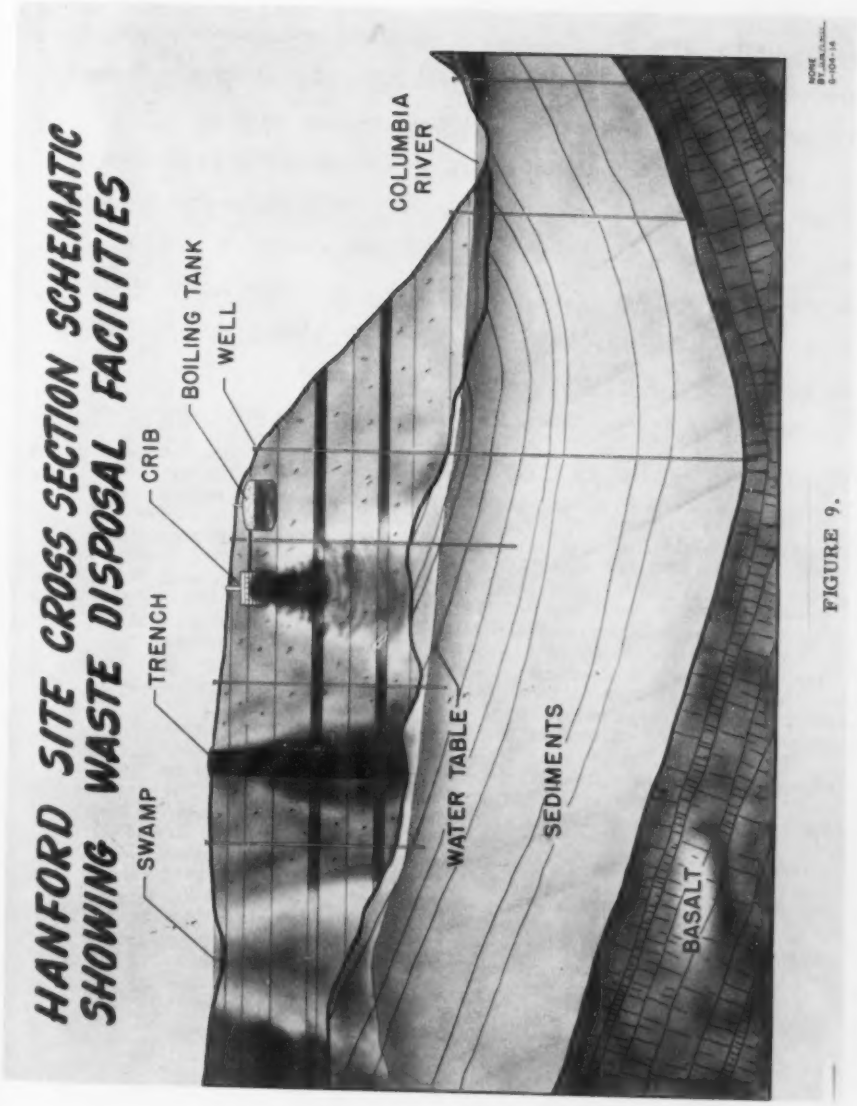

HANFORD SITE CROSS SECTION SCHEMATIC
SHOWING WASTE DISPOSAL FACILITIES
SWAMP
TRENCH
CRIB
BOILING TANK
WELL
COLUMBIA RIVER
WATER TABLE
SEDIMENTS
BASALT

FIGURE 9.

essentially of an insulating disc carrying nine peripherally located pairs of electrodes. Leads from each electrode to the mouth of the well at the ground surface permit measurement of small changes in resistance between the electrodes of each pair. In use the disc is lowered into the well and an electrolyte is introduced into the water at the center of the electrode array; the electrode pair contacted first by the solution is determined by a decrease in the electrical resistance. The azimuthal orientation of the instrument is determined by a gyrocompass mounted in the case housing the disc.

Certain of the hydrological situations are best studied in sand-box models (Figure 10) under the controlled conditions of the laboratory and are more exactly termed "soil physics". One of these concerns the topic of saturated vs. unsaturated flow and is important in considering the mechanism of the movement of liquid wastes and the specific volume of soil contacted by liquids in a given flow system. Solutions discharged to the ground may be expected to move downward toward the ground water table under unsaturated flow conditions, that is, the soil pore spaces will not be completely saturated with solution. After reaching the water table the material merges with the local ground water and moves laterally under the influence of the natural ground water gradient locally present. This lateral movement will be under conditions of saturated flow. The relationships that control saturated water movement are well understood and are stated in the Darcy equation for saturated flow through porous media

$$Q = -KA\,i$$

where: Q = flow of water, gal/day

A = cross-sectional area normal to flow (ft^2)

i = potential energy gradient (ft head/ft)

K = permeability of the formation ($gal/day/ft^2$).

The relationships governing unsaturated movement, on the other hand, have not

FIGURE 10.

been established to the same extent and are much more complex. Research is underway to study the mathematical relationship between moisture content, gradient, and flow rate in different types of soil. It was found that in unsaturated beds of material not all of the liquid present contributes to the general flow of fluid to the same degree. While this work is far from complete, the results indicate the general form that mathematical expression of the various relationships must have and eventually it will be possible to predict the shape of flow patterns beneath the disposal cribs, the amount of waste contained in this zone, and the rate at which wastes will reach the water table.

An additional test of some hydrological parameters was conducted in the field by means of crib disposal of wastes containing a small amount of Co^{60} (half life, 5.2 years). The cobalt was in a chemical form that would not adsorb on soils and therefore acted as a tracer to reveal the movement of the waters (23). This test, which is still in progress, utilizes the monitoring well network and special well facilities to study the distribution of the activity through the ground water.

Processing work with "cold" uranium materials in a plant facility near the river gives rise to certain uranium-containing waste solutions. These are discharged to seepage pits near the river and 30 - 40 feet above the ground water. This situation gave an opportunity to study the effect of shore line discharge to the river. Study of the contamination indicated that the uranyl ion was very little adsorbed onto the soil thus confirming earlier laboratory work. Observations of the behavior of the uranium were also made during the rise and fall of the river by temperature and radioactivity measurements in the water in eighteen wells around the basins and by river traverses and sampling. During the spring high water period (4×10^5 cu.ft./sec. river flow), contamination moved back underground from the basins under the influence

of the reversed gradient as much as one-half mile although the water table gradient was affected up to almost three miles. Decrease in the river stage (to about 6×10^4 cu.ft./sec.) moved detectable uranium back into the river at a point almost one mile downstream from the recharge point. In this same area, studies were made on another occasion of the dilution obtained in the river (17). For the low winter flow, uranium concentrations decreased in less than one mile of the river course to one five-hundredth of the concentration in the water entering the stream. Such studies give at least a partial picture of the behavior of contaminants entering a stream via shore line discharge. Much more complicated and very little studied is the problem of discharge to the river across and along a wide area of the bottom as from solutions rising from depths below the water table. Certainly even more rapid mixing into the river would be obtained under such conditions.

Mineralogy and Soil Chemistry

Studies of the soils have been fundamental to the ground disposal of Hanford radioactive liquid wastes. The principle relied upon is the exchange of the radioactive ion for a non-radioactive ion in the mineral and retention of the former in the crystal. The process is well known and is termed "ion exchange"; other types of retention are recognized, however, and the more general term "adsorption" is sometimes applied.

The Hanford soils are far from uniform and may have widely varying characteristics of grain size, mineral composition, and ion exchange capacity (18). Routine soil samples are periodically taken during the drilling of a well and are retained for such studies as may later be necessary. Significant properties of a soil composite are shown in the following tables.

Typical Hanford Soil
Grain Size

Gravel, >2 mm. 25%

Coarse Sand, 2 - 0.2 mm. 30%

Fine Sand, 0.2 - 0.02 mm. 30%

Silt, 0.02 - 0.002 mm. 10%

Clay, <0.002 mm. 1 - 5%

Mineral Composition

Quartz, feldspar, calcite, mica, augite

Apatite, tourmaline, epidote, opaque minerals

Clay Montmorillonite/kaolinite = 3/1

The collection and interpretation of soil characteristic data is of significance in the identification of geologic formations and the optimum location of waste disposal sites. The identification of certain specific minerals such as clays and calcite is required to understand the mechanism of retention of radioisotopes in soil beds. For example, it was found that although clay minerals generally constitute less than 5% of the soil they are frequently responsible for more than 50% of the exchange capacity. The large capacity of these clays was found to be caused by the preponderance of montmorillinitic clays in this mineral fraction. Such clays are much more active in ion exchange reactions than are other types such as the kaolinites.

The Hanford soils are generally calcareous, ranging up to 15% by weight $CaCO_3$. The soil contains clay ranging from 0 to more than 40% by weight with an average of 1-5%. The cation exchange capacity of the soil ranges from 3 to 80 meq/100 g with an average of 5-10 meq/100 g.

The grain size distribution of the soils was found to influence to a large extent the vertical percolation rate of liquid wastes. Of particular

interest is the "infiltration rate" of liquids into the surface of the soil bed because of its importance in properly sizing pits or cribs for disposal of a given waste stream. Solid material in the wastes and algae or other biological organisms that may develop in disposal structures tend to plug the surface pores of the soil, greatly reducing the effective infiltration capacity of the facility. This plugging effect must be considered in designing the facility and an effort is made to minimize it. In many cases the wastes reduce the infiltration rate of soils through chemical reactions, such as deflocculation of certain kinds of clay or the generation of gas which can plug soil pores and reduce liquid flow. The grain size distribution of each succeeding layer of soil encountered by the wastes moving downward from the disposal crib will largely determine the specific percolation rate for the wastes in that bed and will therefore establish the wetted area necessary to transmit a given flow of liquid. The identification of lenses or beds of relatively low permeability assists with the interpretation of ground water monitoring data, explaining the occasional wide lateral distribution of the liquid.

The ion exchange reactions with samples of Hanford soils were studied intensively for the most prominent, long-lived isotopes occurring in wastes. Studies were made using radiostrontium (19), radiocesium (20), and plutonium (21) among others (22). The pH of the soil-waste system was found to be one of the most significant factors controlling the isotope retention. In general, strontium and cesium were found to exchange best from alkaline solutions, while plutonium was readily removed from solution over a wide pH range, including rather acidic solutions (Figure 11). Both cesium and strontium are less readily adsorbed from solutions containing significant amounts of other salts (Figure 12). It was found that the ability of other ions to compete

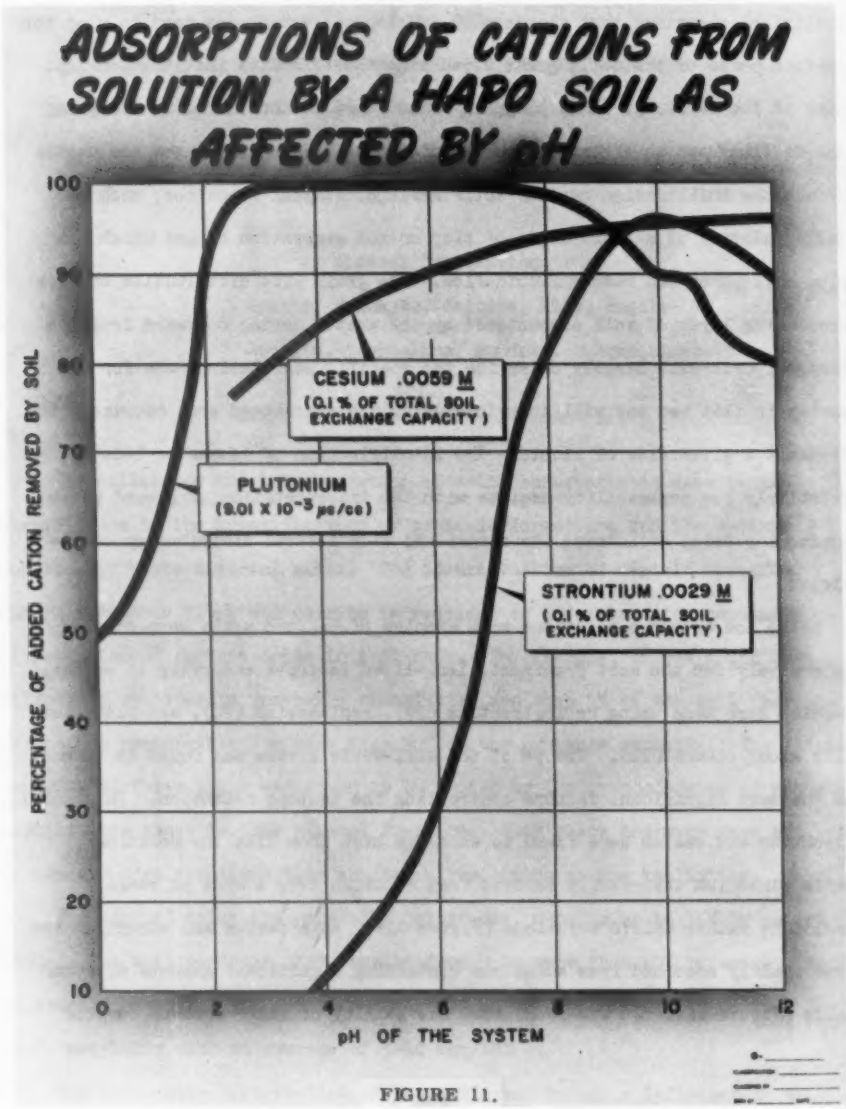

ADSORPTIONS OF CATIONS FROM SOLUTION BY A HAPO SOIL AS AFFECTED BY pH
PERCENTAGE OF ADDED CATION REMOVED BY SOIL
100
90
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
pH OF THE SYSTEM
CESIUM .0059 M
(0.1 % OF TOTAL SOIL EXCHANGE CAPACITY)
PLUTONIUM
(9.01 X 10⁻³ μc/cc)
STRONTIUM .0029 M
(0.1 % OF TOTAL SOIL EXCHANGE CAPACITY)

FIGURE 11.

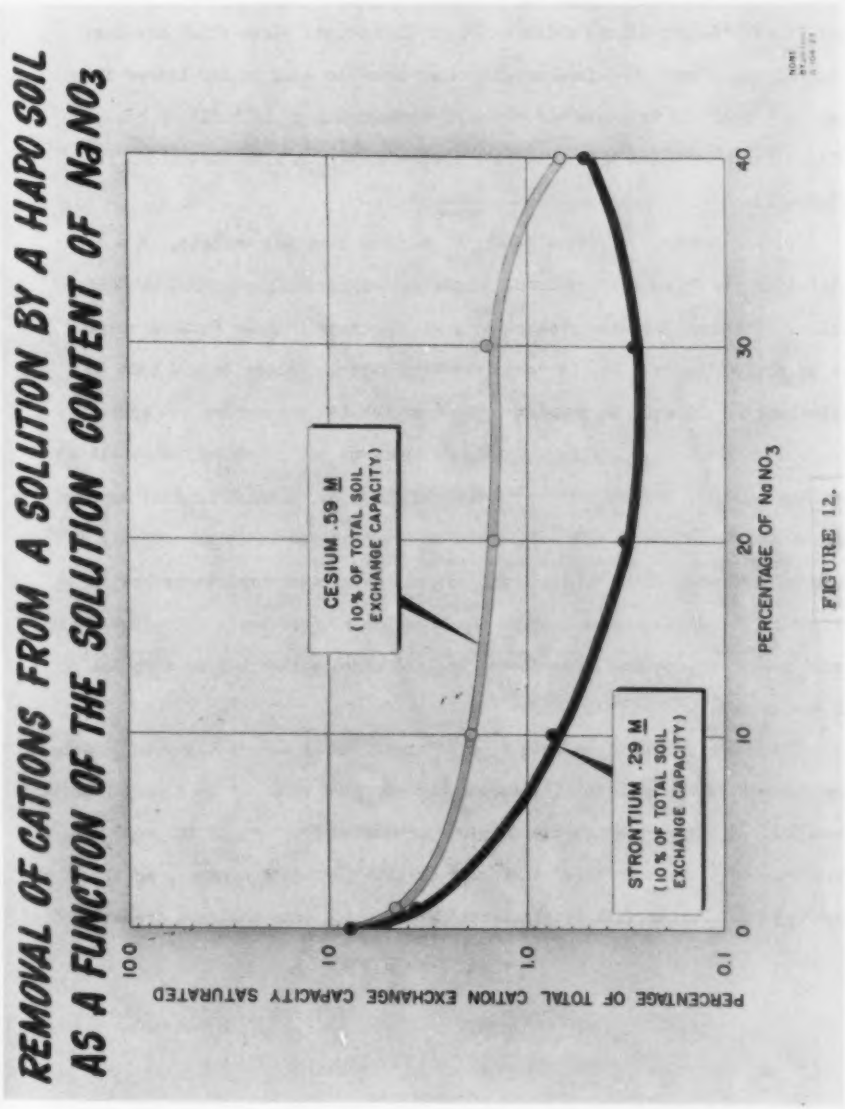

REMOVAL OF CATIONS FROM A SOLUTION BY A HAPO SOIL AS A FUNCTION OF THE SOLUTION CONTENT OF $NaNO_3$
PERCENTAGE OF TOTAL CATION EXCHANGE CAPACITY SATURATED
100
10
1.0
0.1
0
10
20
30
40
PERCENTAGE OF $NaNO_3$
CESIUM .59 M (10% OF TOTAL SOIL EXCHANGE CAPACITY)
STRONTIUM .29 M (10% OF TOTAL SOIL EXCHANGE CAPACITY)

FIGURE 12.

for ion exchange positions on the soil follows the normal lyotropic series, as determined by ionic charge and size.

It is apparent, then, that the ions of the fission products are removed from a solution in a more or less definite sequence by the soil with that one held closest to the disposal point which has the greatest affinity for the soil under the conditions which exist at that point. Ions which are less strongly held must therefore move farther down the soil column before they may exchange. In this way a "volume of contamination" is built up below a disposal facility and this must have a structure much like that shown in Figure 13.

In the presence of certain anions, such as citrate, oxalate, or acetate, plutonium was found to form complex ions not appreciably adsorbed by Hanford soils. For much the same reason Co^{60}, which occurs in some Hanford wastes as an activation product, is "complexed" by various molecules and ions in solution. The resulting complex cations or complex anions are not appreciably removed by the soil. Radioruthenium, an abundant but relatively short-lived fission product, is similarly a neutral molecule or an anion in most Hanford wastes and therefore is not well fixed on the soil and moves essentially as fast as the water which contains it. Knowledge of these relations has served to guide the segregation of plant wastes so that waste solutions which could react to form mobile complexes are not mixed either before disposal or in the ground.

The study of anomalous retention of strontium on some soils when phosphate was present in the solution led to the discovery of what may be a very important reaction. In this reaction the calcium carbonate structure of the soil mineral calcite, $CaCO_3$, is rearranged to form a calcium phosphate mineral, apatite, $Ca_5(PO_4)_3OH$. During this "replacement" process any ions that are present which

CROSS SECTION BENEATH A CRIB
CRIB
GLACIO-FLUVIATILE SEDIMENTS
WATER TABLE
RINGOLD SEDIMENTS

FIGURE 13.

which are chemically similar to calcium, such as strontium, are included in the crystal structure of the new mineral (23). Thus waste solutions containing a small concentration of phosphate are readily decontaminated with respect to radiostrontium when passed through calcite beds or soils containing $CaCO_3$. Preliminary studies have shown that Pu^{+4} will also enter into this reaction. The work will be continued to define the conditions of the reaction more exactly and to show how it may be applied most advantageously. It has been used in Hanford practice by treating wastes with low concentrations of sodium phosphate prior to disposal to calcareous soils.

Work similar to that just described is in progress on Cs^{137} removal. The most fruitful approach to date has been the use of hydrated alkali aluminosilicate minerals of the zeolite family. This family of minerals has the common property of cation exchange under appropriate conditions. Clinoptilolite, $RO \cdot Al_2O_3 \cdot 10SiO_2 \cdot 6H_2O$, and analcite, $RO \cdot Al_2O_3 \cdot 4SiO_2 \cdot 2H_2O$, (where R is a general symbol for exchangeable cation) were found to be highly selective for Cs even in the presence of much larger concentrations of extraneous interfering cations such as Na^{+} or Ca^{++}. These zeolites have many advantages over synthetic exchange resins including greater stability, higher Cs^{137} selectivity in most cases, comparable exchange capacities, and the further possibility of fusing them for permanent fixation. More work will be needed, however, before the use of zeolites for radioisotope fixation can be properly evaluated.

Research is continuing to study the factors that affect the ability of soils to decontaminate actual waste solutions and to develop techniques for testing wastes prior to ground disposal. From early in Hanford history, research was performed by simulation experiments in which wastes were passed through short columns of soil in the laboratory (Figure 14) and the resulting

FIGURE 14.

decontamination was measured by sampling and analyzing the effluent leaving the columns (24,25). For interpreting the data from these tests it is convenient to express the volume of effluent in terms of the volume of soil through which it passed, referred to as "column volumes" of effluent. For the same reason, the degree of contamination is usually expressed as the ratio between the effluent concentration and that of the original waste solution, referred to as the "C/C_o value". The column volumes of effluent passing through a soil column before a certain C/C_o value is achieved is a measure of the soil decontamination ability. A mathematical function of C/C_o was found which provides a linear graph when plotted against the logarithm of the corresponding column volume. This straight line may be extrapolated to permit the determination of flow volumes corresponding to effluent concentrations too small to be rigorously measured by routine methods (26). Such plots are commonly referred to as "break-through" curves.

Since radioactive waste solutions contain a mixture of many radioisotopes, the behavior of each of those present in concentrations large enough to be of concern must be examined. The significance of a given radioisotope in the waste must be considered in the light of its concentration relative to its maximum permissible concentration in potable water. For example, the behavior of Pu^{239}, Cs^{137}, and Sr^{90} would be individually examined in the study of a typical waste discharged to the ground. The relative behavior of the different ions in a waste will depend to a marked degree on the chemical characteristics of the solution and of the soil used, but in a typical situation the first waste constituent that appears in the effluent from a soil column would be the major anion present, such as nitrate ion, followed by radioactive ruthenium, radiocesium, radiostrontium, various rare earth isotopes, and the last to appear, plutonium. The ability of a given soil

to remove each constituent from solution is dependent on the pH of the solution, its total salt content, the chemical nature of accompanying ions or molecules, and the concentration of the ion being studied (25). In some cases small concentrations of stable salts were found to interfere with the removal of specific isotopes by soils; for example, the presence of aluminum ion interferes markedly with the removal of strontium.

The affinity of soils for adsorption of radioisotopes from solution is also studied by means of equilibrium distribution experiments. In this case, a volume of waste and a weighed sample of soil are shaken together for a period long enough to assure the formation of equilibrium conditions in the system. The distribution of specific isotopes between the soil and the liquid fraction of the system is a measure of the capacity of a certain volume of soil for decontaminating that waste. This method eliminates reaction and diffusion rate considerations from the decontamination study and permits the quantitative evaluation of influencing factors. For example, it was thus found that the distribution between soil and solution of both radiocesium and radiostrontium is independent of concentration in the range of interest. Equilibrium studies also revealed the extent to which additives such as corrosion inhibitors, anti-foaming agents, and decontaminating agents affect the retention of radioisotopes on soils (27).

From small scale laboratory tests, predictions are made for plant planning and budgeting purposes of the behavior of actual wastes to be discharged to large disposal facilities (25). Research is in progress to refine the laboratory tests used for this purpose and to evaluate the effectiveness of the estimates. The quantitative influence of individual variables on the breakthrough data from laboratory soil columns is being examined as part of this work. For example, the flow rates used in passing wastes through soil columns were found to have a large effect on the resulting breakthrough curve. The

temperature of the solution charged to a soil column also significantly affects the retention of radioisotopes. This latter influence was shown to be the result of ionic dehydration at elevated temperatures. Such studies of individual physical and chemical variables provide information of value not only to laboratory evaluation tests, but also to understanding optimum design and operating characteristics for ground disposal facilities.

An important activity in support of the waste disposal practice is the analysis of the results from the monitoring activities; valuable information not easily available through laboratory experiment can often be obtained in this way.

Routinely collected monitoring data from wells in the vicinity of ground disposal sites are interpreted by research personnel familiar with the geology, hydrology, and soil chemistry of the region. These analyses identify the source of any radioactive material detected in the ground water near a disposal site and determine its rate and direction of movement. Most waste disposal sites are located in areas in which the water table lies in formations having a low permeability and the observed ground water contaminants move with a velocity of one to two feet per day. The rate of movement of these radioactive contaminants may be much slower than that of the ground water because of the retarding effect of ion exchange with soils comprising the aquifer. Upon occasion radioactive materials have reached much more permeable formations in which their observed rate of movement may be as great as a hundred feet per day. This rapidly moving contamination is always composed of those chemical species that tend to form neutral molecules or negatively charged ions in solution such as ruthenium or cobalt and which do not appreciably adsorb on Hanford soils. These isotopes are of relatively short half-life and are not of great radiological concern. In these rapidly moving aquifers the concentrations of radioactive material found in well

samples is always very low, frequently barely in the detectable concentration range and usually less than 0.1% of the Maximum Permissible Concentration (28) in drinking water. The uniform reduction of concentration in these rapidly moving aquifers may well be the result of rapid movement occurring in only a thin layer or single filament of the total aquifer, becoming mixed with quantities of slower moving, uncontaminated water during the sampling process. Special in-well tests have shown the degree to which ground water velocities at different levels in the soil can result in "stratification" of the contaminants in the ground water. The possibility of denser waste solutions sinking in the natural ground water is under study. The results of laboratory tests of waste reactions with soil together with these analyses of ground water movement are used to design and establish well sampling schedules.

Samples of wastes are routinely tested in the laboratory by means of soil columns to predict the life of cribs and to assist with monitoring interpretations. Recommendations are provided for the proper location of new disposal sites on the basis of soil chemical, hydrologic, and laboratory soil column data. Laboratory tests with actual wastes provide information regarding the proper chemical treatment of these wastes for optimum retention of the radioactive material by soils. For example, these tests disclosed the need for neutralization of one condensate waste stream to assure adsorption of radiostrontium by the soil.

A final example of the application of this ion exchange research is found (18) in a study which combined the average ion exchange capacities of the soils from wells across the site, Figure 15, with the depths to ground water (or "isopachs") at those positions, Figure 16. The result, Figure 17, was a map of contours illustrating a single-valued "capacity factor". This has been of value in optimizing the location of new disposal facilities and husbanding the ground disposal resources available for this purpose.

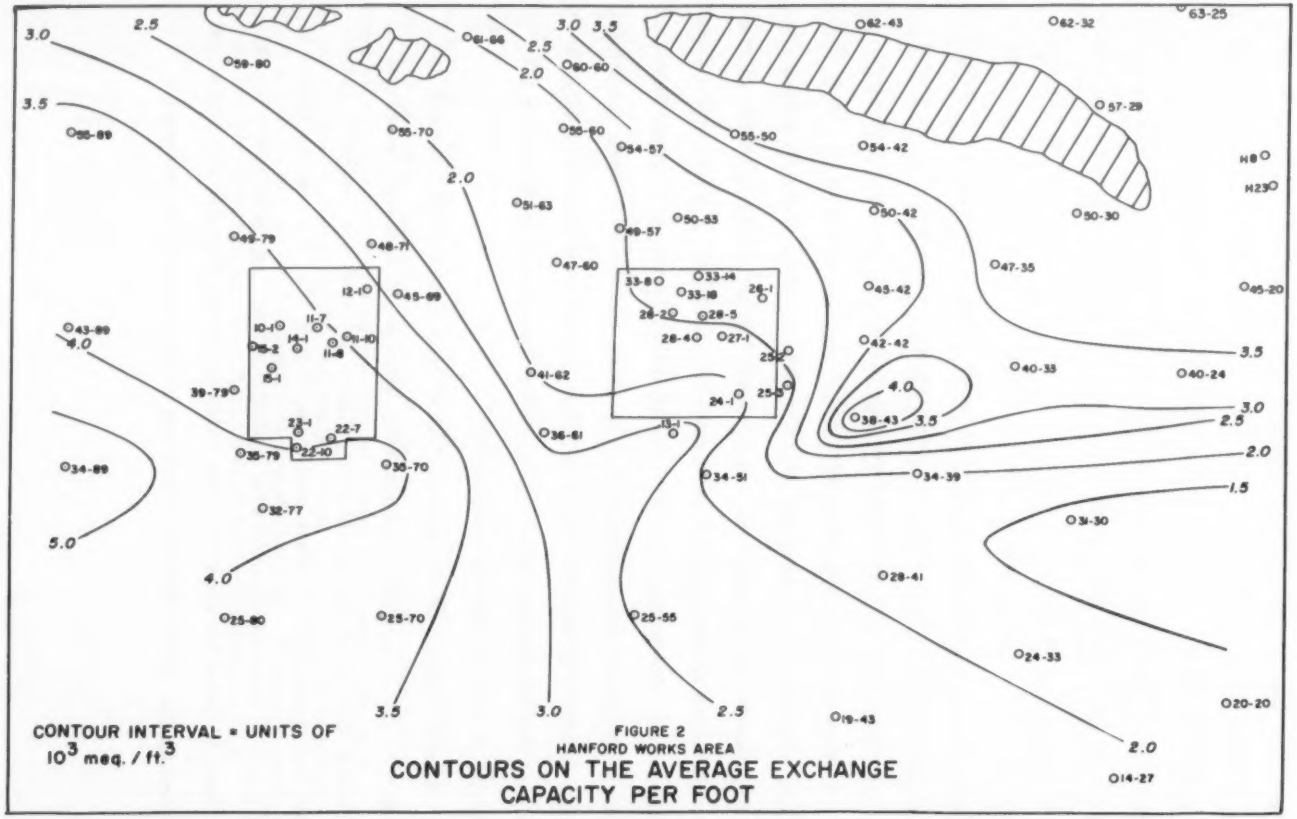

CONTOUR INTERVAL = UNITS OF
10³ meq. / ft.³
FIGURE 2
HANFORD WORKS AREA
CONTOURS ON THE AVERAGE EXCHANGE
CAPACITY PER FOOT

FIGURE 15.

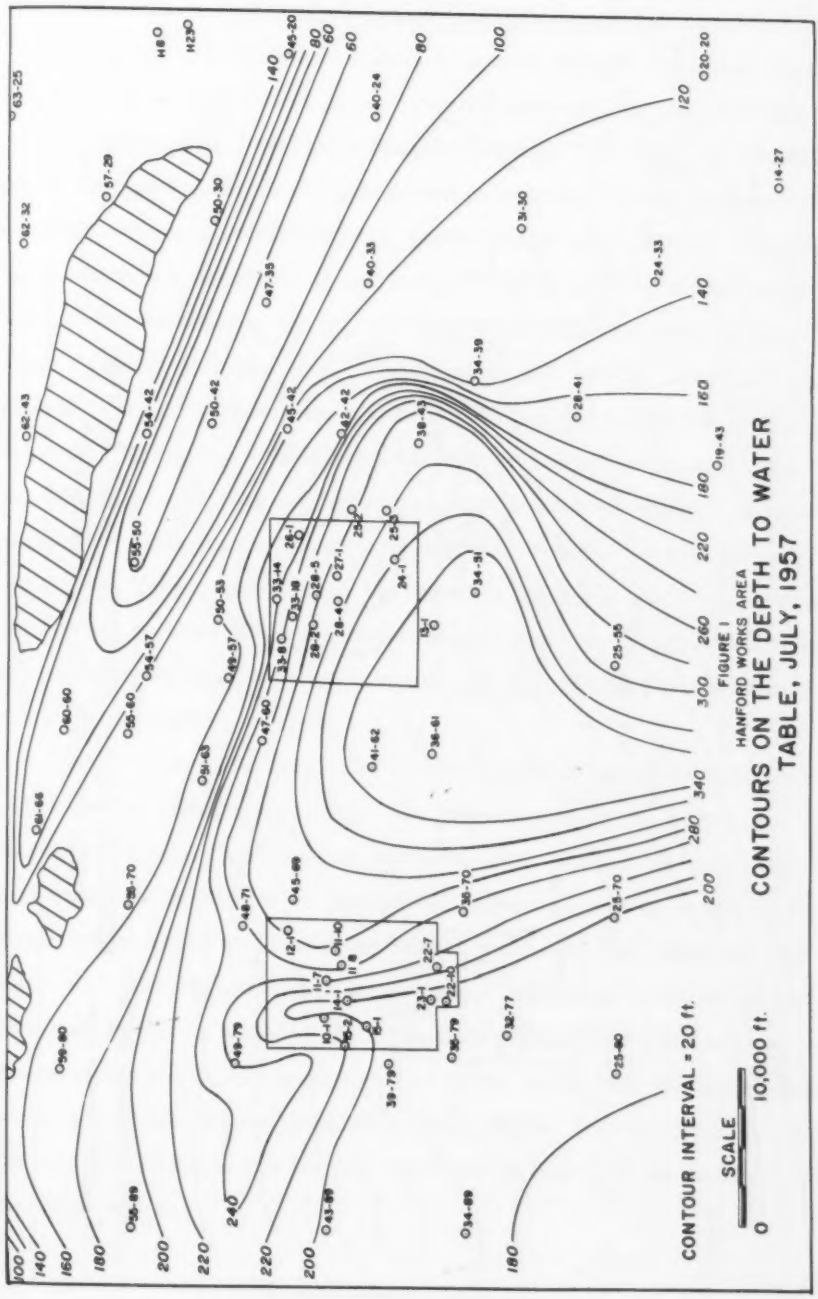

CONTOURS ON THE DEPTH TO WATER TABLE, JULY, 1957
HANFORD WORKS AREA
FIGURE 1
CONTOUR INTERVAL = 20 ft.
SCALE
0
10,000 ft.

FIGURE 16.

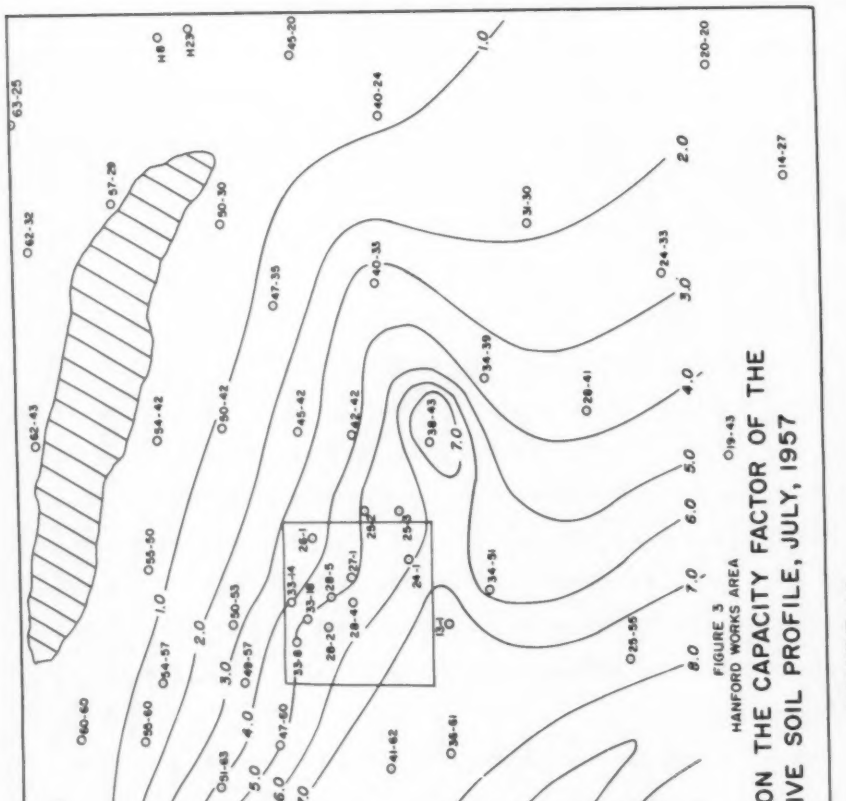

CONTOURS ON THE CAPACITY FACTOR OF THE EFFECTIVE SOIL PROFILE, JULY, 1957
CONTOUR INTERVAL = UNITS OF 10^5 meq./ft.^{2}/profile depth
FIGURE 3
HANFORD WORKS AREA

FIGURE 17.

Analytical Chemistry and Instrumentation

Monitoring wells located adjacent to ground disposal facilities, storage tanks, or at any point where ground water contamination is suspected are sampled according to a carefully designed schedule. The frequency of sampling and the analyses required are established on the basis of well location with respect to disposal sites, character of the wastes being monitored, and previous monitoring experience in the vicinity. Most of these monitoring wells are 8 inches in diameter and all are cased with perforated steel casings. Routine samples are taken from the wells using pint pottles lowered in steel holders on a cable. The ground water is generally 200 to 400 feet beneath the top of the casing. For special analyses it may be necessary to obtain and combine several such samples to give sufficient total volume. Routine samples are taken with a frequency of once a week, twice a month, or once every three months, depending on the significance of the well. All of these samples are analyzed for gross concentration of beta-emitting radioisotopes and selected ones from critical locations are analyzed for the significant individual isotopes.

Routine analyses of monitoring samples are performed with established radiochemical techniques (29, 30). The radioactivity of the sample is measured with laboratory counting equipment, beta emitting isotopes with thin-window Geiger-Mueller or proportional counters and those having suitable gamma-ray components in their decay radiation through their gamma-ray emission. The sensitivity with which these radiochemical analyses may be performed depends on the size of the sample available, the total soluble solids in the sample, the total activity of the sample, and the radiochemical properties of the isotope being determined. Typical routine detection limits for monitoring samples and the respective MPC values (28) are shown in the following tables.

Detection Limits -
Routine Monitoring Samples

Isotope	Detection Limit uc/cc
Gross Beta Particle Emitters	2×10^{-7}
Cobalt-60	8×10^{-7}
Strontium-90	2×10^{-7}
Ruthenium-106	7×10^{-7}
Cesium-137	7×10^{-7}
Uranium-238	1×10^{-9}
Plutonium-239	1×10^{-7}

Some Maximum Permissible Concentrations

Isotope	Half-life	MPC, water, uc/cc
Cobalt-60	5.2 yr	4×10^{-4}
Strontium-90 + Yttrium-90	28 yr	8×10^{-7}
Ruthenium-106 + Rhodium-106	1.0 yr	1×10^{-4}
Cesium-137 + Barium-137	30 yr	2×10^{-3}
Cerium-144 + Praseodymium-144	285 d	1×10^{-4}
Promethium-147	2.6 yr	2×10^{-3}
Uranium-238	4.5×10^{9} yr	2×10^{-6}
Plutonium-239	24×10^{3} yr	3×10^{-6}

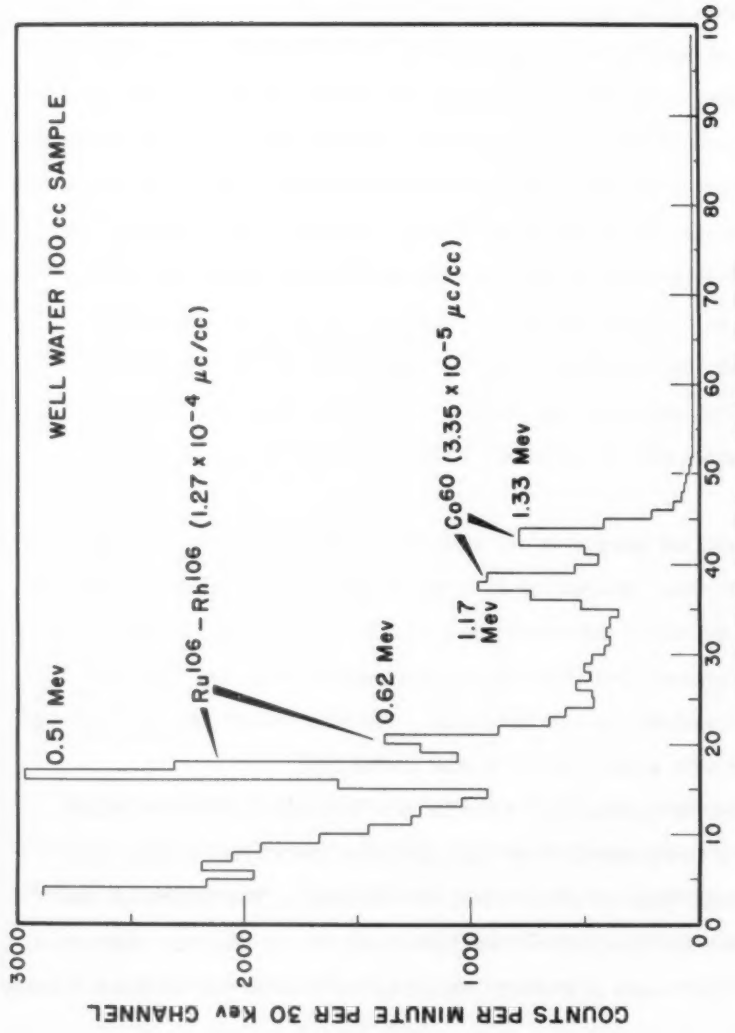
Considerable research effort has been devoted to the development of more sensitive and accurate methods, techniques, and instrumentation for the identification and measurement of radioactive isotopes in waste streams. Areas of notable advancement have been the application of gamma scintillation spectrometry and low level beta counters, and the prototyping and application of in-line automatic samples and analyzers. Effective late in 1958 the routine laboratory detection limit of Sr^{90} was lowered to 7.0×10^{-8} uc/cc.

Availability in recent years of reliable commercial multichannel analyzers has greatly aided progress in gamma scintillation spectrometry. These instruments sort out and record pulses from a source into from tens to hundreds of energy channels, covering the full gamma spectrum. This permits extensive, highly resolved data from the scintillation detector.

In Figure 18 is shown a chart record of a well water sample obtained with a 100-channel gamma ray spectrometer. The location of the "peak" on the horizontal energy scale identifies the isotope while the area bounded by the peak shows the relative intensity and this is interpreted in terms of concentration present. The figure shows the determination of 1.27×10^{-4} uc Ru^{106}/cc and 3.35×10^{-5} uc Co^{60}/cc in a standard 100 cc sample. The sensitivity obtainable in such a sample is 4.3×10^{-7} uc/cc for Ru^{106} - Rh^{106}, 1.3×10^{-7} uc/cc for Co^{60}, and about 1×10^{-7} uc/cc for Cs^{137} depending on the Ru content. Greater sensitivity may be obtained if larger samples are used; for example, one hundred times the sensitivity can be obtained with a sample of 10 liters evaporated to a volume of 100 cc.

An excellent example of the versatility and sensitivity of gamma-ray scintillation spectrometry is a system for the analysis of river water for eleven prominent gamma-emitters (31). No radiochemical separation is necessary; ordinary radiochemical methods require about ten times the manpower to achieve the same precision. The same methods are used for the analysis of well waters and soils when needed (29).

Very low background beta counters have been developed. One counter system has a background of less than one count per minute, a value one-twentieth that found in conventional beta counters. The instrument consists of four gas flow proportional beta chambers shielded with six inches of steel. Background is further reduced by surrounding the counting chambers



GAMMA RAY SPECTRUM

FIGURE 18

with fourteen long Geiger-Mueller tubes and providing an anti-coincidence circuit. The latter rejects events (such as from cosmic rays) which give simultaneous pulses in the GM tubes and the beta proportional counters.

The reduction in background to the low value described permits great sensitivity in the analysis of pure beta-emitters such as Sr^{90}. Using this counter system, a procedure was developed for the analysis of well water samples. In order to eliminate certain interferences, Sr^{90} is determined through separating and counting the Y^{90} daughter, also a pure beta-emitter. A sensitivity of 8×10^{-9} uc/cc (about 1% of the MPC) can be achieved using a sample of 250 cc, and greater sensitivity with a larger sample.

Various types of automatic samplers have been developed and applied to waste streams. A "multiweir" sampler (32) was installed in the Purex plant. This sampler splits out a known aliquot of the waste stream passing to the disposal site. Sampling is accomplished by first dividing the total flow into 25 equal streams, diverting one of the 25 and dividing it in turn into 100 streams, one of which is retained for analysis.

Other sampling devices of greater complexity have been applied. One of these is a sampler which removes a proportional sample by means of a dipper of carefully dimensioned proportions. The sampler rests above a weir box through which the water flows and the rate is recorded as the height of water above the weir. From the weir flow equation, the dipping sampler is designed to remove the water sample on a controlled cycle in an amount proportional to the flow rate of the stream.

Still other samplers deliver a fixed volume on signal from an automatic time switch controlling a solenoid valve in the line. The use of these and other types of samplers gives assurance that representative portions of the stream are taken for analysis.

FIGURE 18

Significant accomplishment has been achieved in the area of automatic instruments which sample and analyze radioactive constituents present in waste streams disposed to the river or leading to the atmosphere. One such instrument rapidly detects low levels of fission products released to a process stream. Another instrument samples a stream, prepares the sample dish, delivers and evaporates the sample, determines the gross beta particle emission rate and records the result. This sampling is repeated on a fixed cycle. A third instrument samples a stream, makes simple chemical separations, and measures and records the radioactivity of the several isotopes present (33). Application of instruments such as these to ground disposal problems is under study.

Process Engineering

In the large scale processing of nuclear materials for the recovery and decontamination of uranium and plutonium, substantial waste stream volumes are produced which have a relatively low radioisotope content in addition to the relatively small volumes of high level wastes. Some waste streams which are normally completely inactive may inadvertently become contaminated by the failure of a heat transfer surface such as the wall of a pipe carrying steam for evaporative operations or water for cooling. Also, there are streams which become contaminated by entrainment from boiling or gas-sparged radioactive solutions.

It is desirable to minimize these volumes of contaminated solutions which are destined for ground disposal as well as to decrease their content of radioisotopes. For purposes of identification these waste streams are classified in the following in descending order of potential for contamination.

Process Condensates are the condensates or "overheads" obtained from the boiling or evaporating of radioactive solutions for ad-

justing concentrations in the process or reducing volumes before disposal as a waste. Volatile and entrained fission products are present in proportion to their concentration in the "bottoms".

Steam Condensates are streams which result when the steam used for the heating medium in an evaporating process is condensed. These have potential for being highly contaminated through failure of the heat transfer surface separating the heating medium from the radioactive solution being heated. Corrosion resistance of the materials of construction, fabrication quality, and the concentration and composition of the solutions being heated determine the probability, frequency, and severity of such contamination.

Process Coolants are the water streams used as the cooling medium to condense evaporator overheads and to control the temperature of process solutions. The causes and extent of contamination of these streams are the same as those for steam condensates; however, the probability of contamination is much less here because of the minimum corrosion rates under the lower temperature conditions. In addition, the coolant used for condensing evaporator overheads has the least potential of becoming contaminated because of the low order of isotope content in the condensed vapor. However the volume of such coolants is likely to be great.

Process improvements which are being used to reduce the volume and contaminant concentrations of the condensate-type waste streams include the segregation of streams to avoid cross-contamination. In the plant processes, for example, the condensate streams are kept separate from the cooling water stream; this permits discharge of the essentially uncontaminated cooling water to a swamp while the generally contaminated condensate stream is sent to a crib. At one separations plant an earlier practice of combining cooling

water and steam condensate caused low level contamination of a swamp. The combined system was replaced with separate disposal systems, a new swamp provided for the cooling water and the previous one back-filled.

A second type of improvement has been the provision of continuous monitoring of in-plant streams to detect excessive contamination. Automatic monitors instantly detect contamination increases due to equipment failure and allow immediate corrective maintenance, thereby decreasing the amounts of radioactive materials that would otherwise go to the ground.

Wherever possible, recycle and re-evaporation or rework of low activity waste streams has been incorporated into the process. In this manner, it has been possible to avoid the disposal of thousands of curies of radioisotopes to ground facilities. In support of continued efforts in this direction, modifications are being made to return the Purex tank farm condensate to the process. This change will further reduce the discharge to the ground by approximately 500 curies per month.

In order to obtain optimum conditions for ion-exchange of the fission products with the soil it is necessary to avoid dilution of the waste streams whenever possible. In the past, contact condensers were employed for some streams. This type of condenser mixes the cooling water with the condensed vapors; this results in undesirably large dilution. This type of condenser is being replaced by surface condensers which do not mix the coolant and the condensing vapors but accomplish the condensing through a heat transfer surface. Thus excessive dilution is avoided, the innocuous coolant is sent to a swamp, and the condensate is handled separately.

Always of concern are the consequences of a heat transfer surface failing and permitting concentrated solutions of radioisotopes to leak into process steam and process cooling water systems. Consequently, automatic

continuous pressurization of heat transfer surfaces has been incorporated. In this manner, the pressure within the process steam system is always maintained higher than the hydrostatic pressure of the radioactive solutions. If a leak develops, flow will be from the uncontaminated to the contaminated stream, and undesirable contamination of solutions destined for ground disposal will be minimized.

Further reduction of contamination from waste streams is under continuing study. Such processes as those involving ion exchange techniques, closed cycle cooling systems, and chemical scavenging processes are being studied along with evaporative processes. Improvements in sampling and monitoring techniques are similarly under continual study. Equipment and techniques discussed in other sections of this presentation such as the continuous analyzing monitor for reactor effluent, proportional samplers, improved analytical methods, and chemical processes for fission product fixation show considerable promise as aids in reducing the radioactivity of wastes disposed to the ground.

DWP:hsf

Disposal to the Ground
List of References

1. (a) Brown, R. E., Pearce, D. W., et al. Experience in the Disposal of Radioactive Waste to the Ground at Two Production Sites. Submitted for the 1958 International Conference on Peaceful Uses of Atomic Energy.

   (b) Pearce, D. W. and Honstead, J. F. Radioactive Waste Disposal at Hanford. Presented at the 13th Purdue Industrial Waste Conference, May 1958.

2. Brown, R. E., Parker, H. M., and Smith, J. M. Disposal of Liquid Wastes to the Ground. Proc. Internat. Conf. Peaceful Uses of Atomic Energy. 9, 669-75 (1956).

3. (a) Brown, R. E., McConiga, M. W., and Rowe, P. P. Geological and Hydrological Aspects of the Disposal of Liquid Radioactive Wastes. Sanitary Engineering Aspects of the Atomic Energy Industry. TID 7517 (Pt. 1B) 413-25 (1956).

   (b) Brown, R. E. Geological Conditions at Hanford Works Regulating the Disposal of Radioactive Liquid Wastes to the Ground. Trans. Am. Geophys. Union. Abstract 38, 2, 269 (1957).

4. (a) Brown, R. E. Role of Geology at the Hanford Works, Washington. Bull. Geol. Soc. Am. Abstract 67, 12 (Pt. 2), 1762 (1956).

   (b) Brown, D. J. and Brown, R. E. A Subsurface Aeolian Deposit at the Hanford Project, Washington. Reported to Cordilleran Sect., Geol. Soc. Am. March 1958.

5. Brown, R. E. and Brown, D. J. Surface of the Basalt Series in the Pasco Basin, Washington. Reported to Cordilleran Sect., Geol. Soc. Am. March 1958.

6. Raymond, J. R. A Shaped Charge System for Well Casing Perforating. HW-57675, October 1958.

7. Raymond, J. R. Applicability of Geophysical Methods of Exploration at Hanford Atomic Products Operation. HW-38707, August 1955.

8. (a) McConiga, M. W. Deformation of the Ringold Formation. HW-36373, April 1955.

(b) McConiga, M. W. and Brown, R. E. Deformation of the Ringold Formation. Geological Soc. Am. (submitted for publication).

9. Brown, R. E. and Bierschenk, W. H. Geological and Hydrological Guides to the Ground Containment and Control of Wastes at Hanford. Reported to 4th Nucl. Engrg. and Sci. Conf. 1958. To be submitted for publication in Mining Engineering.

10. Bierschenk, W. H. and McConiga, M. W. Changes in the Hanford Water Table 1944-1957. HW-51277, July 1957.

11. Raymond, J. R. and Bierschenk, W. H. Hydrologic Investigations at Hanford. Trans. Am. Geophys. Union 38, 5, 724-9 (1957).

12. (a) Bierschenk, W. H. The Effect of Ground Water Mounds on the Purex Operation. HW-49728, April 1957.

(b) Bierschenk, W. H. Hydrological Aspects of Radioactive Waste Disposal. J. of the Sanitary Engineering Division, Amer. Soc. of Civil Engineers, Nov. 1958, Paper No. 1835-1.

13. Raymond, J. R. A Pumping System for Groundwater Aquifer Evaluation. HW-51171, June 1957.

14. Bierschenk, W. H. Hydraulic Characteristics of Hanford Aquifers. HW-48916, March 1957.

15. Rowe, P. P. Difference Approximations to Partial Derivations for Uneven Spacings in the Network. Trans. Am. Geophys. Union. 36, 6, 995-1008 (1955).

16. Haney, W. A., and Honstead, J. F. A History and Discussion of Specific Retention Disposal of Radioactive Liquid Wastes in the 200 Areas. HW-54599, Jan. 1958.

17. Haney, W. A. Dilution of 300 Area Uranium Wastes Entering the Columbia River. HW-52401, Sept. 1957.

18. McHenry, J. R. and Honstead, J. F. Evaluation of Sites for the Disposal of Radioactive Waste Solutions. HW-53219, Nov. 1957.

19. (a) McHenry, J. R. Adsorption and Retention of Strontium by Soils of the Hanford Project. HW-34499, Feb. 1955.

(b) McHenry, J. R. Ionic Exchange Properties of Strontium in a Calcareous Soil. Soil Sci. Presented at the Soil Sci. Soc. of America meeting November 1957.

20. McHenry, J. R. Adsorption and Retention of Cesium by Soils of the Hanford Project. HW-31011, March 1954.

21. (a) Rhodes, D. W. Preliminary Studies of Plutonium Adsorption in Hanford Soil. HW-24548, May 1952.

(b) Rhodes, D. W. Adsorption of Plutonium by Soil. Soil Sci. 84, 465-71 (1957).

22. McHenry, J. R. Rhodes, D. W., and Rowe, P. P. Chemical and Physical Reactions of Radioactive Liquid Wastes with Soils. Sanitary Engineering Aspects of the Atomic Energy Industry. TID-7517 (Pt. 1A) 170-90 (1956).

23. Ames. L. L., McHenry, J. R., and Honstead, J. F. The Removal of Strontium from Wastes by a Calcite-Phosphate Reaction. Submitted for the 1958 International Conference on Peaceful Uses of Atomic Energy.

24. (a) Rhodes, D. W. and Nelson, J. L. Disposal of Radioactive Liquid Wastes from the Uranium Recovery Plant. HW-54721, June 1957.

(b) McHenry, J. R. The Removal of Cesium-137 and Strontium-90 from Scavenged Bismuth Phosphate Solutions. HW-48141, Feb. 1957.

25. (a) Rhodes, D. W., Raymond, J. R., and Clukey, H. V. Operational Experience in Hanford Liquid Waste Disposal. Sanitary Engineering Aspects of the Atomic Energy Industry. TID-7517 (Pt. 2) 5-22 (1956). Classified.

(b) Brandt, H. L. and Reisenauer, A. E. The Influence of Limestone Neutralization on the Soil Uptake of Sr^{90} from a Radioactive Waste. HW-56582, Aug. 1958.

26. Brandt, H. L. Calculation of Purex A-8 Crib Capacity. HW-51399, July 1957.

27. Knoll, K. C. Effect of Detergents Upon Adsorption of Radioisotopes in Soils. HW-52055, Aug. 1957.

28. Hanford Atomic Products Operation Radiation Protection Standards. HW-25457, Rev. 1; Appendix A.

29. (a) Healy, J. W., Thorburn, R. C., and Carey, Z. E. H.I. Control Laboratory Routine Chemical Procedures. HW-20136, 1951.

(b) Silker, W. B. An Analytical Method for the Determination of Radioactive Cesium. HW-29959, Nov. 1953.

(c) Silker, W. B. A Continuous River Sampling System and Methods of Radiochemical Analysis for Strontium-89, 90, Barium-140 and Phosphorus-32. HW-47578. Jan. 1957.

(d) Thomas, C. W. Radiochemical Analysis of Bravo Shot Soil Samples. HW-38987, Jan. 1957.

30. (a) Schwendiman, L. C. Standard Practices Counting Manual. HW-30492, Jan. 1954.

(b) Norton, H. T., Jackson, P. O., and Reid, D. L. Standard Practices Radiochemical Calculation Manual. HW-46436, Nov. 1956.

31. Perkins, R. W., and Nielsen, J. M. Gamma-Ray Spectrometric Systems of Analysis. Submitted for the 1958 International Conference on the Peaceful Uses of Atomic Energy.

32. Honstead, J. F. Proportional Waste Line Sampler. US Pat. 2,800,797. July 30, 1957.

33. Schwendiman, L. C., Rieck, H. G. and Harvey, R. A. Automatic In-Line Analyzers for Radioactive Constituents in Liquid and Gaseous Waste Streams. Submitted for the 1958 International Conference on Peaceful Uses of Atomic Energy.

DISPOSAL OF RADIOACTIVE LIQUID WASTES IN TERRESTRIAL PITS - A SEQUEL

By

W. de Laguna, K. E. Cowser, and F. L. Parker* (See p. 1204)

INTRODUCTION

Pits dug in the earth to receive liquid radioactive waste for disposal may function either as storage basins or as ion exchange columns, as explained by Struxness, Morton and Straub when they reported on the early experience with waste disposal pits at Oak Ridge.[1] The concept of the pit as a tank has been largely abandoned, for few if any earth materials are sufficiently impermeable. The three waste disposal pits now in use at Oak Ridge are of value not for their storage capacity, but for the ability of the soil around them to trap and hold the radioactive constituents in the waste as it seeps out. The total amount of waste that such pits can handle and the safety of their operation, depend on how good an ion exchange column is provided by the earth around the pits. This is a difficult question, for the answer depends on a detailed knowledge of the hydraulic and chemical properties of an underground mass of rock which, in most cases, is far from homogeneous.

The waste pits at Oak Ridge have the following advantages: first, they provide secure storage, for the waste cannot be released suddenly from the clay as it could be from a ruptured tank; and second, the cost is much less than for tank storage. The disadvantage of the pits is the inability to determine just what is happening to the waste or how its component elements may disperse. For this reason there is some question in the minds of most of the members of the Committee on Waste Disposal of the National Academy of Sciences as to the long-term safety of the disposal method, and they specifically recommend that continuing disposal of large volumes of low-level waste in the vadose zone, above the water table, be of limited application because it probably involves unacceptable long-term risks.[2]

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* Oak Ridge National Laboratory, Operated by Union Carbide Corporation for the U. S. Atomic Energy Commission.

The study of the waste disposal pits at Oak Ridge has suggested modifications of their design which will improve their operating characteristics and reduce the exposure to radiation of the men who must work with them. To date no radioactive strontium or cesium, the two most hazardous nuclides, have been found in the waste escaping from the pits, although it is probably present in the neighboring streams in amounts too small to detect. Therefore, the present authors feel that the pits have so far been a success, although we would not recommend an increase in the scale of the operation until experience has provided more information on the long-term problem.

PRESENT OPERATING PROCEDURES

At present there are three pits in service. They are arranged end to end on the crest of a low ridge and are operated as a unit. (See Figure 1.) Each pit is roughly 200 feet long, 100 feet wide, and 15 feet deep, and has a nominal capacity at the 12-foot stage of one million gallons. Table I shows the volumes of waste that have been pumped to each of the pits, and Table II shows the total amounts of the more important radionuclides. At present, every ten days or so a batch of roughly 80,000 gallons of waste is pumped into pit 3. Enough is retained in Pit 3, which leaks very slowly, to maintain its stage at about 12 feet; the balance is overflowed into Pit 2. Pit 2 also is maintained at about the 12-foot stage, and the balance, if any, is overflowed into Pit 4. In summer, when evaporation is high, Pits 3 and 2 can dispose of all the waste. In winter, some must be run into Pit 4 (see Figure 2). Pits 3 and 2 are kept filled because their shale sides have adsorbed much cesium, and when they are exposed the radiation field in the area increases markedly. Once, when the stage of Pit 3 was lowered 3 feet, the radiation field at the edge increased to 5 r per hour. Generally it is much less. The radiation field 100 feet back from the pit is commonly in the order of 25 to 50 mr per hour.

Pit 4 is generally dry in the summer and is only partly filled in the winter. The waste which has so far reached Pit 4 has been relatively low in cesium 137, in part because of dilution by rain water in Pits 3 and 2, in part because of adsorption onto the walls of the first pits. With time, however, the radiation field around Pit 4 has also increased to the point where a serious problem has developed. At present, working time in the pit area must be limited to a few hours per week, but this depends greatly on location.

To understand how the pits are working and to predict possible future developments, a budget must be maintained to determine the distribution and destination of the various components in the waste. Indeed, three budgets are desirable - liquid, chemical, and radiochemical. The liquid budgets for Pits 2 and 3 must consider: (a) waste pumped or transferred to the pit, (b) waste transferred to the next pit, (c) changes in volume in storage, (d) gains from rainfall, (e) losses from evaporation, and (f) losses from seepage. The first four items can be measured directly,

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TABLE I

VOLUMES OF WASTE DISCHARGED TO PITS - GALLONS

Year	Pit 2	Pit 3	Pit 4
1952	42,900	---	---
1953	235,100	---	---
1954	909,600	---	---
1955	639,000	1,035,000	---
1956	1,270,300	201,400	1,307,500
1957	797,500	-577,900	2,682,000
		TOTAL	8,542,400

TABLE II

AMOUNTS OF RADIOACTIVE MATERIALS DISCHARGED TO PITS - CURIES

Radioactive Materials	Curies	
Ru^{106} and Rh^{106}	20,000	
Cs^{137} and Ba^{137}	75,000	
Sr^{90} and Y^{90}	2,000	
Others	3,000	
	TOTAL	100,000

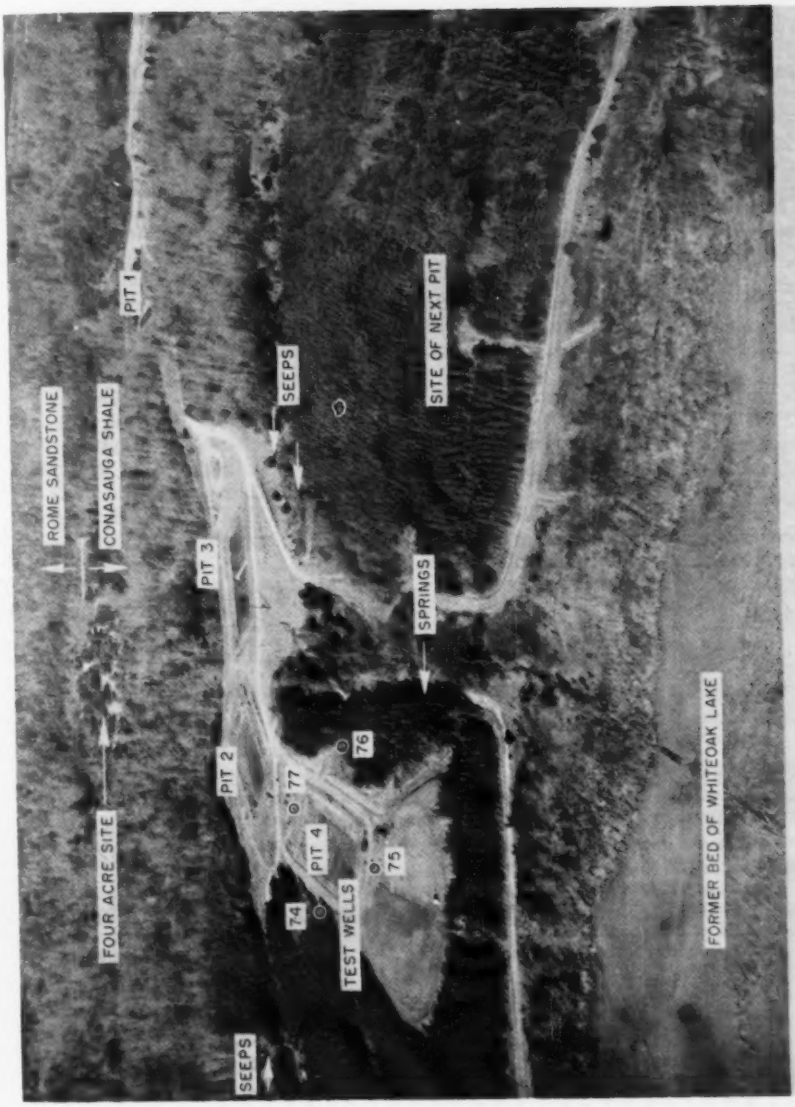

Figure 1. Aerial View of Waste Pits.

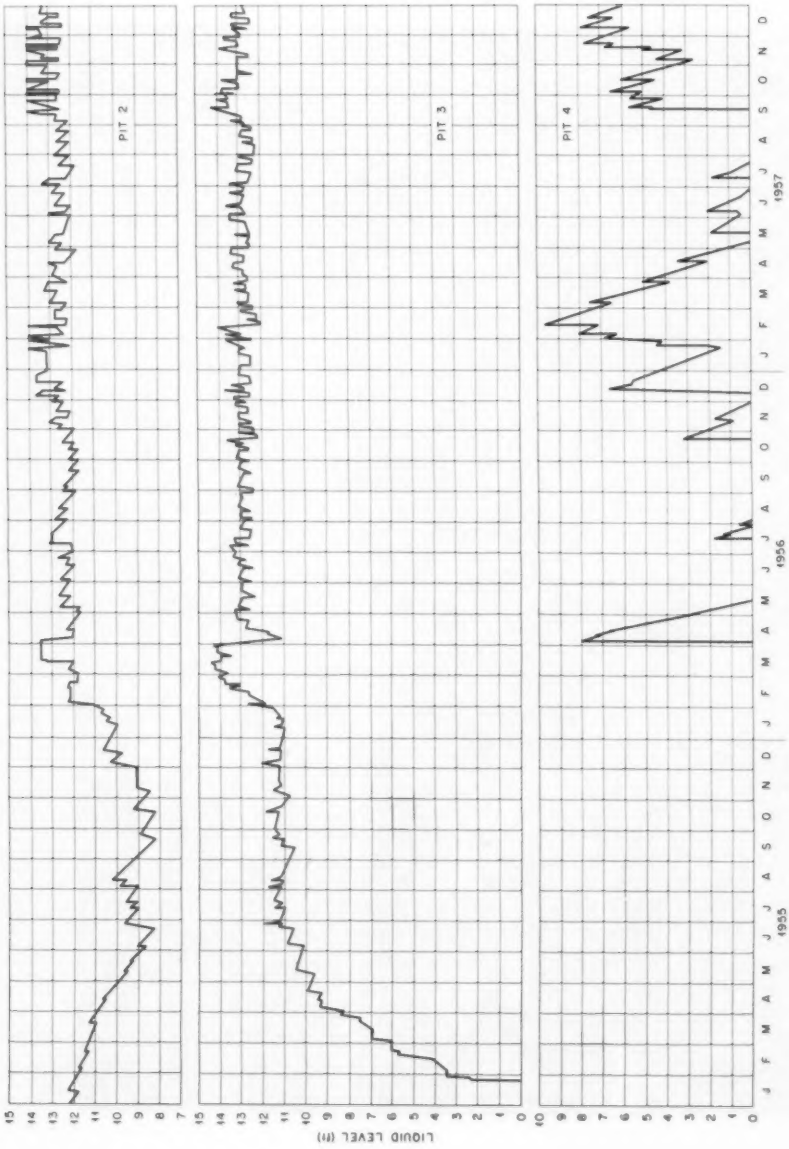

Figure 2. Liquid Levels in Pits.

although the volumes transferred between pits are not as accurately known as we would wish. The evaporation loss from a small lake is seldom easy to determine,[3] but the problem is harder still in a pit filled with radioactive liquid, because of the difficulty of installing and operating the required instrumentation. (See Figures 3 and 4). Therefore, it has been necessary to estimate evaporation from the observed losses from several evaporation pans. Evaporation was also calculated by the use of a semi-empirical formula developed by Kohler.[4] Despite the active co-operation of the local United States Weather Bureau, the determinations of evaporation have never been entirely satisfactory. Seepage, which is the most important factor in the liquid budget, cannot be measured directly for Pits 2 and 3, and must be calculated as the difference between the other items. Pit 4 leaks so rapidly that other factors may be neglected.

During the first few months of operation the bottom of a new pit becomes nearly sealed with mud and sludge which settle out of the waste. Following this, the permeability of the shale around the pits does not appear to change, and one must infer that there is little entrainment of silt, swelling of the clay, or leaching of carbonate from the shale by the moving waste. The seepage rates are some 15 to 20 per cent higher in summer than in winter, probably due to changes in viscosity of the waste with temperature.

Some progress has been made in maintaining a budget or materials balance for the stable chemical and radioactive nuclides in the waste, but a complete accounting is not yet available. Data from cores drilled near the pits would be required; this is not practical to obtain because of the radiation exposure hazard. The total amounts of the various waste components going into the pits are fairly well known, and sampling at White Oak Dam, past which flows the drainage from the pits, gives a measure of the amounts leaving the controlled area; but it does not now appear possible to give in detail the distribution of the materials retained in and around the pit system.

Table III shows the liquid budgets for Pits 2 and 3 for 1956, a typical year.

Pit 2 lost 1,450,000 gallons by seepage, or an average of 3,900 gallons a day, but because rainfall exceeded evaporation by about 450,000 gallons the net liquid loss was only 950,000 gallons. Pit 3 lost about 375,000 gallons by seepage, or roughly 1,000 gallons a day. However, for Pit 3, the rainfall increment exceeded evaporation losses by about 375,000 gallons, so there was no net liquid loss or gain for Pit 3. This pit serves a useful purpose for the liquid that seeps away carries some radioactive materials out into the shale, and more are adsorbed onto the shale sides of the pit; rain water dilutes the remainder.

Figure 2. Liquid Levels in Pits.

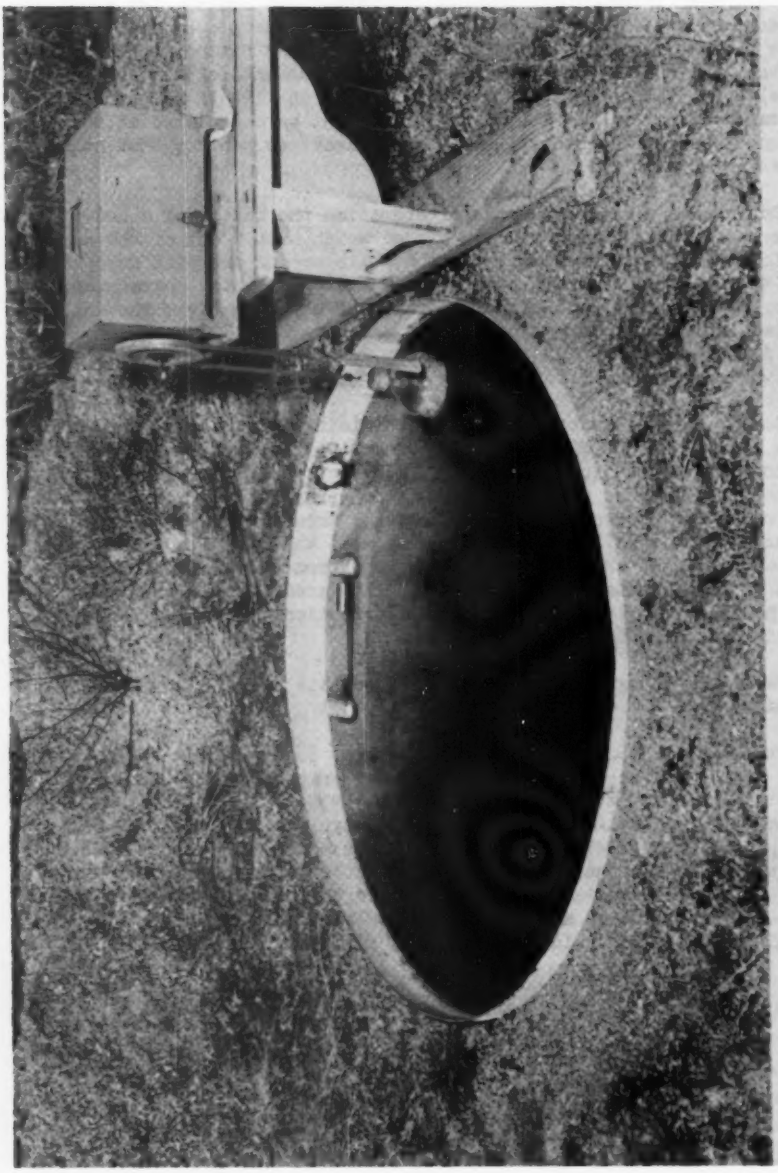

Figure 3. Evaporation Pans.

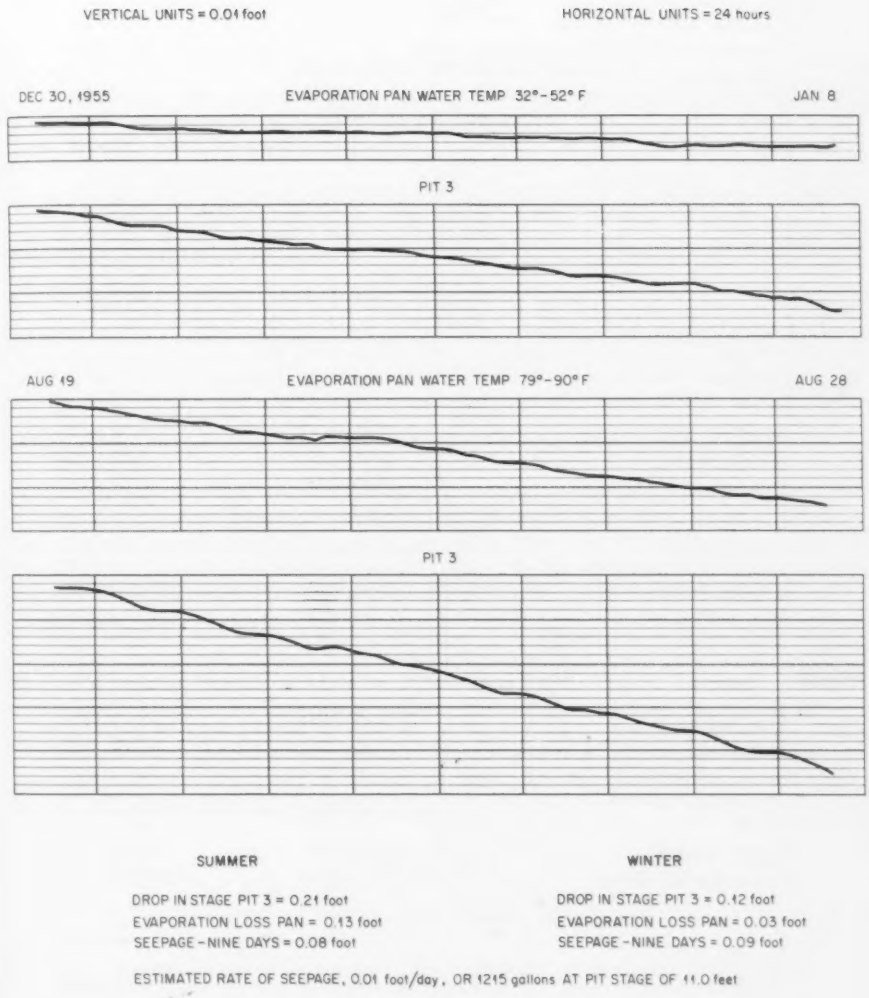
VERTICAL UNITS = 0.01 foot
HORIZONTAL UNITS = 24 hours
DEC 30, 1955
EVAPORATION PAN WATER TEMP 32°-52° F
JAN 8
PIT 3
AUG 19
EVAPORATION PAN WATER TEMP 79°-90° F
AUG 28
PIT 3
SUMMER
DROP IN STAGE PIT 3 = 0.21 foot
EVAPORATION LOSS PAN = 0.13 foot
SEEPAGE - NINE DAYS = 0.08 foot
WINTER
DROP IN STAGE PIT 3 = 0.12 foot
EVAPORATION LOSS PAN = 0.03 foot
SEEPAGE - NINE DAYS = 0.09 foot
ESTIMATED RATE OF SEEPAGE, 0.01 foot/day, OR 1215 gallons AT PIT STAGE OF 11.0 feet

Figure 4. Seepage Determinations.

TABLE III

LIQUID BUDGETS, PIT 2 AND 3, 1956

(Figures in Gallons)

	Pit 2	Pit 3
Losses		
Pumped out	1,300,000	2,600,000
Evaporated	250,000	350,000
Change in storage	300,000	250,000
Gross Loss	1,850,000	3,200,000
Gains		
Pumped in	2,600,000	2,850,000
Rainfall	700,000	725,000
Gross Gain	3,300,000	3,575,000
Less Gross Loss	-1,850,000	-3,200,000
Seepage	1,450,000	375,000

GEOLOGY OF THE PIT AREA

To explain the hydrology of the pits, it will be necessary to describe briefly the geology of the pit area. The Oak Ridge area is underlain by four principal rock units which are repeated by thrust faulting. These are: the Rome sandstone and the Conasauga shale of Cambrian age, the Knox dolomite, partly Cambrian and partly Ordovician in age, and the Chickamauga limestone of Ordovician age. A cross section of the general area is shown in Figure 5.

The waste pits are excavated in weathered Conasauga shale, a light brown, layered and banded weak rock which is much broken by many little joints into small prisms. The approximate texture and composition are shown in Table IV.

Weathering extends to a depth of 30 to 40 feet under the low ridges and to a depth of about 10 feet under the valleys; in many places the bottom of the weathered zone is roughly at the water table. The fresh shale below is composed of thin alternating layers of hard, dark-gray calcareous shale and light-gray shaly limestone. Much of the carbonate is leached out by the weathering; in general the limestone layers are turned into silty clay and the shale layers into a fine silty sand.

In general the shale dips to the southeast at about 35°, but there are several types of structure which complicate this simple pattern. At the north end of Pit 3 (see Figure 6) a reversal of dip has produced a small anticline and syncline; the width of the structure is about 150 feet. The dips are gentle and there is no evidence of crumpling or faulting. In the area occupied by Pit 4 the beds are intensely and irregularly folded and crumpled (Figure 7). Exposures suggest that this belt of crumpled beds is roughly 200 feet wide and that it extends east and west along the strike for at least 1000 feet. There is some hydrologic evidence, discussed below, which suggests that this belt of crumpled rock is bordered on the south by a fault, possibly a thrust fault related to the Copper Creek fault. South of Pit 4, and south of the presumed fault, there are a number of small folds. Exposures in and near Pit 2 are poor, but it appears probable that there are no folds or faults in this area.

MOVEMENT OF WATER IN THE CONASAUGA SHALE

The weathered shale is much more permeable than the fresh shale. Water moves through the altered rock along the many joints, and as these are more closely spaced and more regular along the bedding planes, the water moves much more easily parallel to the strike than at an angle to it. There is some movement of water through the fresh shale, not through the rock itself but along joints and fractures. Figure 8 shows the results of testing, by short vertical sections, some of the observation wells near Pit 4, using water under pressure. The mc

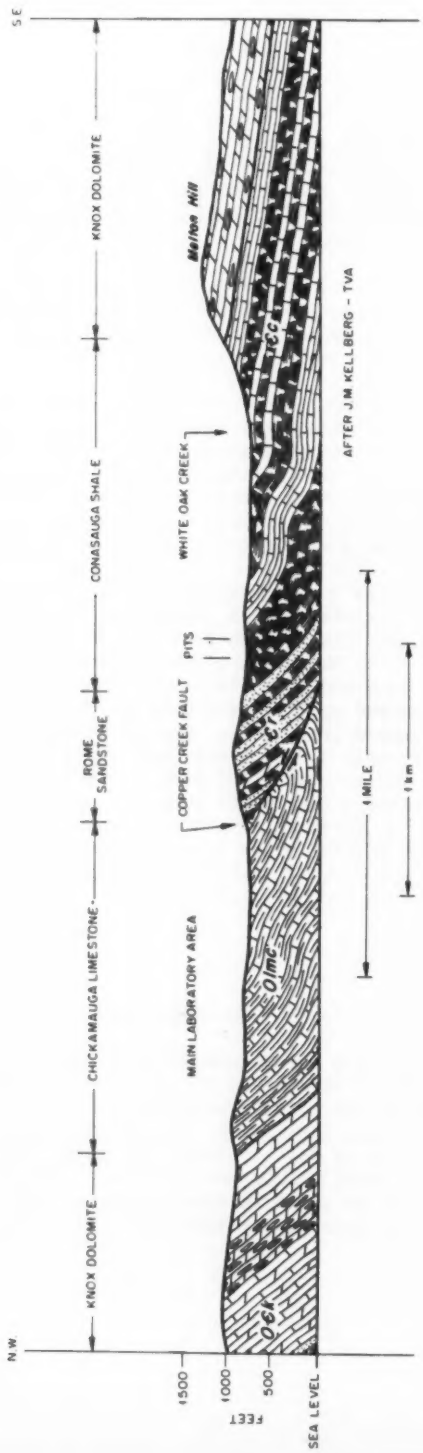

Figure 5. General Geologic Cross Section.

TABLE IV

WEATHERED GRAY SHALE

Texture				Composition of Clay Fraction		
Fine Sand	Very Fine Sand	Silt	Under Clay	Illite	Kaolinite	Quartz
.10 - .25mm	.05 - .10 mm	.002 - .05mm	.002mm	---	---	---
1 to 10%	4 to 25%	45 to 70%	10 to 40%	45 to 95%	Trace to 40%	5 to 25%

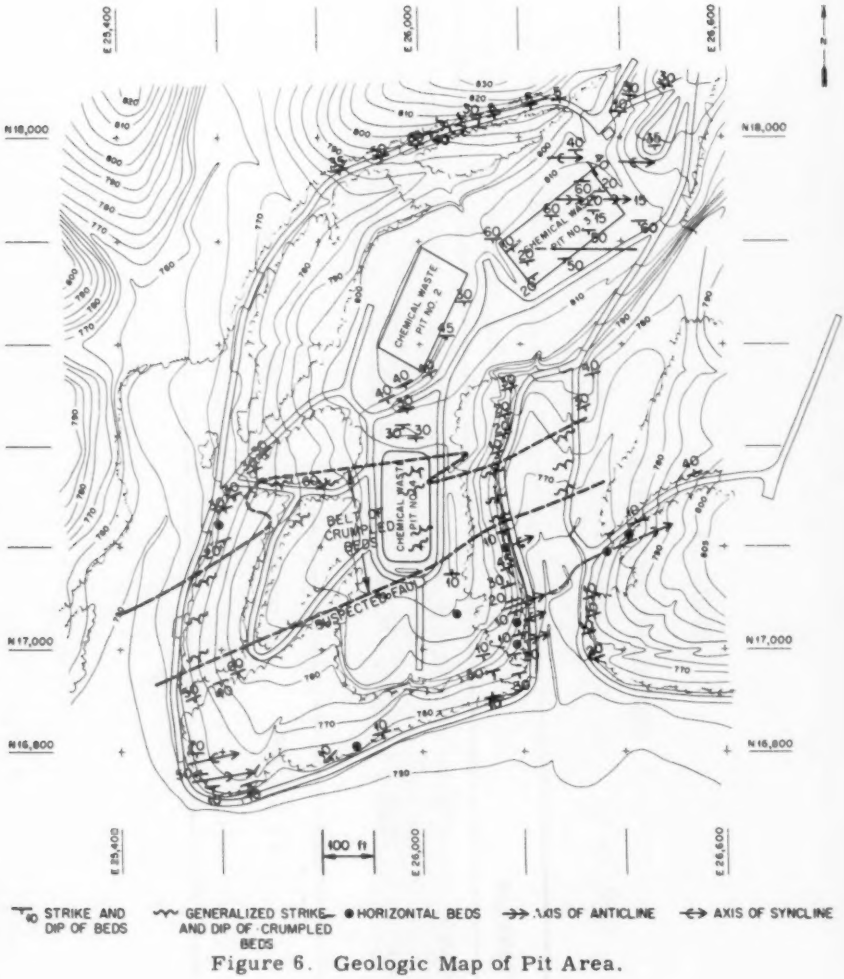

Figure 6. Geologic Map of Pit Area.

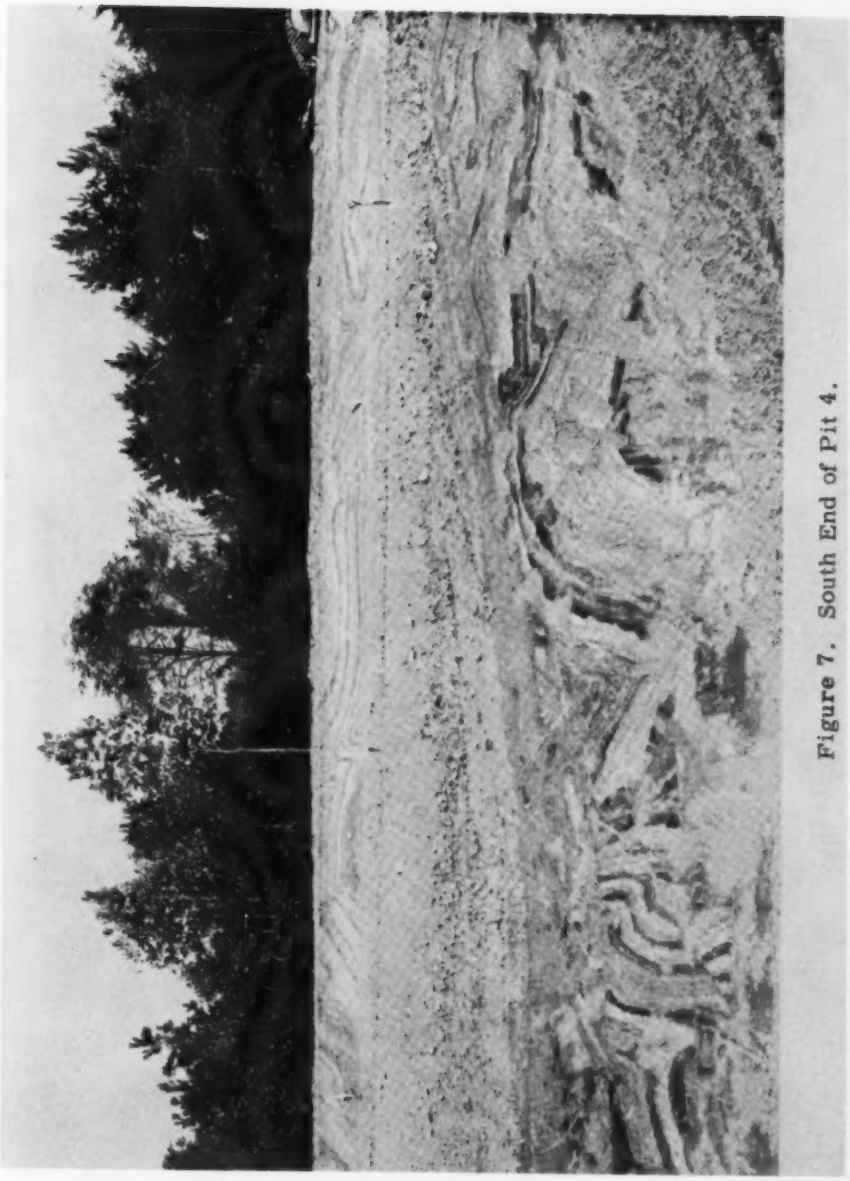

Figure 7. South End of Pit 4.

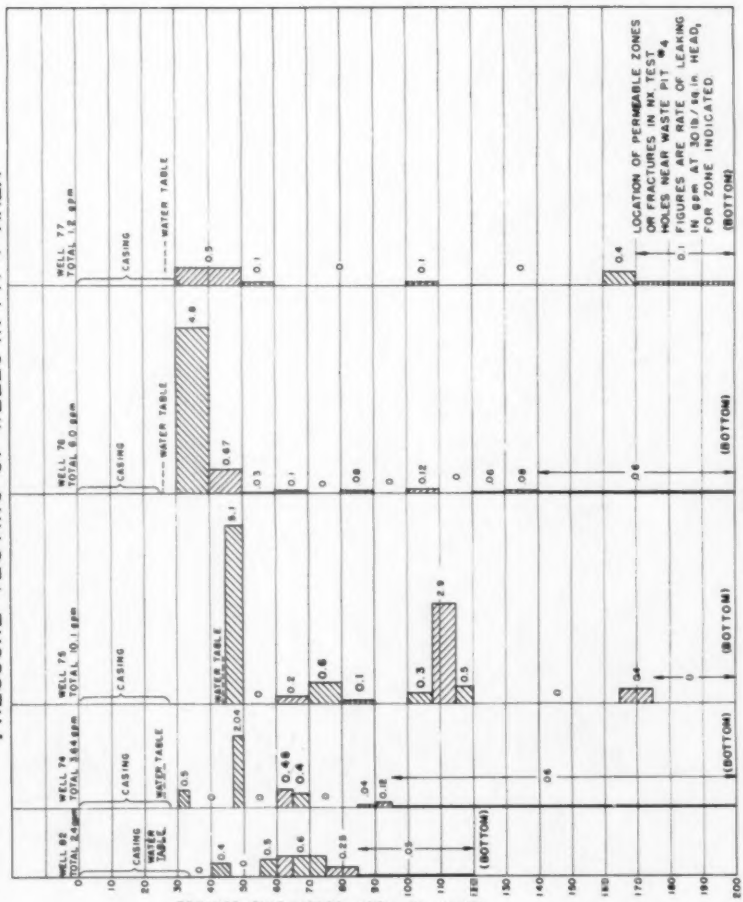
PRESSURE TESTING OF WELLS IN PIT 4 AREA
DEPTH IN FEET BELOW LAND SURFACE
WELL 82
TOTAL 2.4 gpm
WELL 79
TOTAL 38.4 gpm
WELL 75
TOTAL 10.1 gpm
WELL 76
TOTAL 60 gpm
WELL 77
TOTAL 12 gpm
CASING
WATER TABLE
(BOTTOM)
SCALE, RATE OF LEAK, IN gpm
LOCATION OF PERMEABLE ZONES OR FRACTURES IN NX TEST HOLES NEAR WASTE PIT #4
FIGURES ARE RATE OF LEAKING IN gpm AT 30 lb/sq in HEAD, FOR ZONE INDICATED

Figure 8. Pressure Testing, Pit 4 Area.

permeable section of the fresh shale is near the top; there are some fractures down to 100 feet, but apparently very few below 200 feet. This method does not test the permeability of the weathered shale for the test wells are cased down to fresh rock.

Several pumping tests were made both at the site of Pit 4 before the pit was built, and at a proposed pit location about a quarter mile to the north called the Four Acre Site, underlain by similar shale but where the geologic structure is much simpler. The Four Acre Site was at one time considered as a possible location for a high-level waste disposal pit, but the idea was abandoned largely as the result of the work described below. The purpose of the pumping tests was to try to determine the pattern of movement of ground water through the shale as a guide to the possible future movement of waste. The method has several defects for pretesting a proposed pit site, and the data obtained must be used with caution. A seepage pit raises the water table in its vicinity, increasing the thickness of weathered shale through which the liquid flows; pumping lowers the water table. A more important defect in the method is that a pumping test provides data on changes in water level which can be converted into volumes and rates of movement only in the case of an isotropic and homogeneous aquifer, which the shale most certainly is not. Still, much of value was learned. Drawdowns of comparable wells at the Four Acre Site and the Pit 4 site suggested that the shale in the Pit 4 area was more permeable, and although no other data permits a second direct comparison, the rapid leaking of Pit 4 shows the shale here probably has an unusually high permeability.

In each test a group of five wells was used, a central pumped well, and four observation wells at equal distances out from the center. The observation wells were located across the bedding from the central well, one to the north (No. 77) and one to the south (No. 75), and parallel to the bedding, one to the east (No. 76) and one to the west (No. 77). At the Four Acre Site the water levels in the north and south wells changed hardly at all, confirming our belief that waste would move through the shale almost entirely in the direction of the bedding. At the Pit 4 site the water levels in the north and south wells showed a very marked response, (see Figure 9) but a detailed analysis of the data suggested that here too the movement of waste would be parallel to the bedding. The water level in the north well (No. 77) rose for several hours after the pumping started, due to the slight deformation of the rocks in the area resulting from the removal of water around the pumped well. Similar changes in water level were produced in thin-bedded limestones just to the north,[5] and show that the water is present in the rock in many very thin fractures of small total porosity. After some hours of pumping the water level in the north well did begin to fall, but the delay suggests that the permeability of the shale across the bedding in this area is low.

The water level in the south observation well (No. 75) in the Pit 4 area dropped several feet as a result of the pumping, and this large response suggested that the shale in this direction might be permeable at right angles to the bedding. Pressure testing had shown that there is a

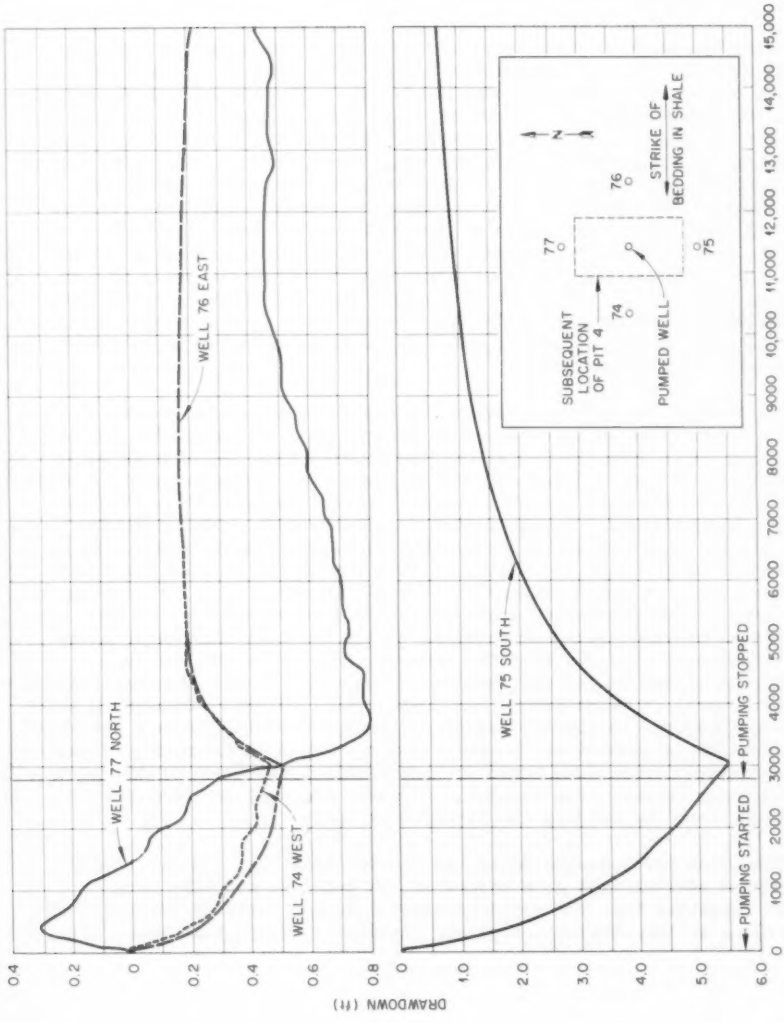

Figure 9. Pumping Test, Pit 4 Area.

permeable zone in the well at a depth of 110 feet; the first thought was that a fracture extended up along the bedding and intersected the pumped well. Later, the construction of the pit showed that the bedding is far too contorted to support this explanation. Further pumping tests in which the lower part of the observation well (No. 75) was sealed off and measured separately, showed that there is no hydraulic connection at the deeper level and water flowing to the pumped well moves out through the fractures located 50 feet from the surface, just below the water table. One tentative explanation advanced at the time was that the shale to the south of Well 75 was particularly impermeable, so that little water could move in to replace that lost to the pumped well. Subsequent events have tended to substantiate this hypothesis, and the barrier is now believed to be a fault.

Further testing provided more information about the movement of water through the shale, but in every case more problems were created than were solved. For example, during a pumping test at the Four Acre Site a tracer was introduced into one of the observation wells 200 feet out along the bedding on strike from the pumped well. The tracer consisted of a mixture of sodium chloride, sodium nitrate, water and methanol, a mixture with a density equal to that of the ground-water, a most important consideration in quantitative ground-water studies. Figure 10 shows the pattern of arrival of the tracer at the pumped well. The central well was pumped at a rate of one gallon a minute. The tracers were first seen in water from the pumped well after 80 hours. After 280 hours of pumping the chloride and nitrate content in the pumped water were still increasing, and about 8.7 per cent of the tracer had come through. At least 1000 hours of pumping, and perhaps much more, would have been required to pull essentially all the tracer through. The rapid first appearance of the tracer, as compared to the total time it was present in the water from the pumped well, (so different from what is seen in tests in homogeneous aquifers), suggests that some of the tracer moves rapidly through relatively permeable and direct channelways, while some follows less permeable and more devious routes. This is not a desirable condition in a potential ion exchange column.

The conclusion is that it is virtually impossible to predict from any known method of pretesting, in a proposed site in the Oak Ridge area, how a waste disposal pit will operate. In a pumping test the response of the water levels in the observation wells may be due to pressure effects or to the actual removal of water; the magnitude of the response depends on the hydraulic connection with the pumped well, the hydraulic connection with outlying areas which may supply water to replace that removed, and on the porosity. These factors cannot always be separated. The only reliable test is to fill the pit with water before putting waste into it. Sodium chloride added to the water in the form of rock salt could be used as a tracer, but even this would supply little information on the possible future patterns of movement of radioactive waste.

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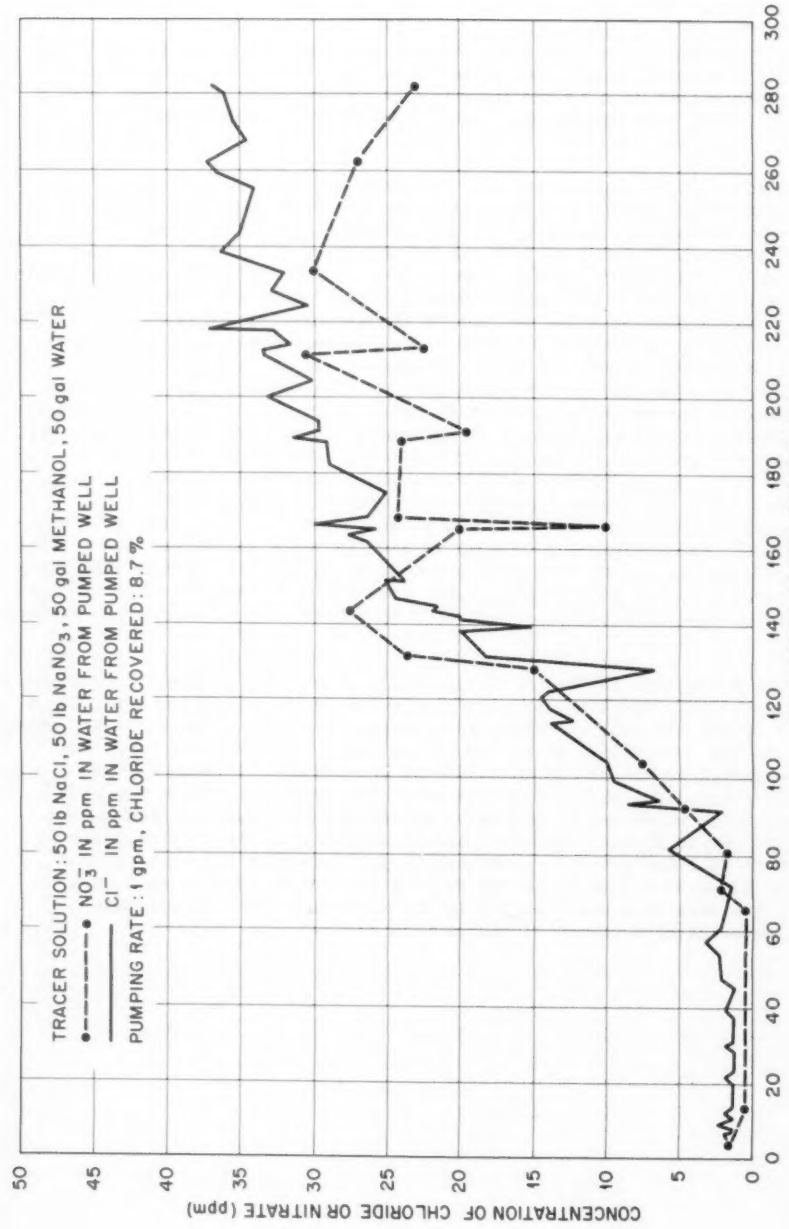

Figure 10. Tracer Test, Four Acre Site.

Figure 10. Tracer Test, Four Acre Site.

HYDROLOGIC CHARACTERISTICS OF THE OPERATING PITS

Figure 11 shows the water table on January 10, 1958. For over a year prior to this time the waste levels in Pits 2 and 3 had been maintained at close to the 13-foot stage, and the water table had stabilized around the pits (see Figure 2). Pit 4 was put into service in April 1956, and by the end of 1957 it had received more than four million gallons of waste. The water table around Pit 4 is never stable. Waste is run into the pit in batches, usually during the winter months, and it is impossible to maintain any fixed liquid level in the pit. When the level is fairly high the waste leaks out rapidly; 20,000 gallons a day at the 8-foot stage. When the stage falls the rate decreases. At the same time the water table rises under and around the pit, water-table gradients are steepened, and the rate of movement of liquid out from the pit area increases. (See Figure 12). When the pit stage falls and the rate of leaking from the pit decreases, the water table rises less rapidly until eventually an equilibrium is reached. When the pit is empty the water table falls until more liquid is added to the pit. The water-table map of January 10, 1958, was made at a time when there had been liquid in Pit 4 for some time, and the water table mound under the pit was approximately at a maximum. The stage of Pit 4 at this time was 4.6 feet, and the pit was leaking at a rate of about 16,500 gallons a day.

Assuming that all three pits were roughly in equilibrium with the water table around them, it is possible to estimate the permeability of the weathered shale through which the bulk of the waste is moving.

The waste is moving out from Pit 4 almost entirely along the strike east and west; there is certainly no movement to the north, if only because of the water-table gradients outward from Pit 2. The very small amounts of activity found in the observation wells to the south show that no important volume of liquid is moving in this direction. Because the pit was not full, the effective length of the pit was roughly 150 feet. The thickness of saturated weathered shale is roughly 30 feet, and the water-table gradient in the direction of movement about 10 feet in 100. This gives a permeability of 18 gallons per day per square foot at unit gradient. (Meinzer's units) (300 ft. x 30 ft. = 9000 sq. ft.; 16,500 gpd at gradient 0.1 = 165,000 gpd at unit gradient; 165,000 gpd/9000 sq. ft. = 18 gpd at unit gradient).

Pit 2 is leaking to the west along a zone about 200 feet wide; to the east it is partly blocked at Pit 3, so that the zone of leakage is roughly 100 feet wide. Assuming the same depth to bedrock, a water-table gradient of 15 feet in 100, and a rate of leakage of 3900 gpd, the permeability of the weathered shale is 2.9 gpd in Meinzer's units. The shape of the ridge forced Pit 3 to be oriented more nearly parallel to the bedding than is desirable, and consequently only 150 feet of bedding is intersected, and much of the potential zone of leakage to the west is blocked by Pit 2. Assuming that the zone of leakage has a total length of 200 feet, a depth to bedrock of 30 feet, a gradient of 15 feet in 100, and a rate of leakage of 100 gpd, the permeability of the weathered shale around Pit 3 is 1.1 gpd in Meinzer's units.

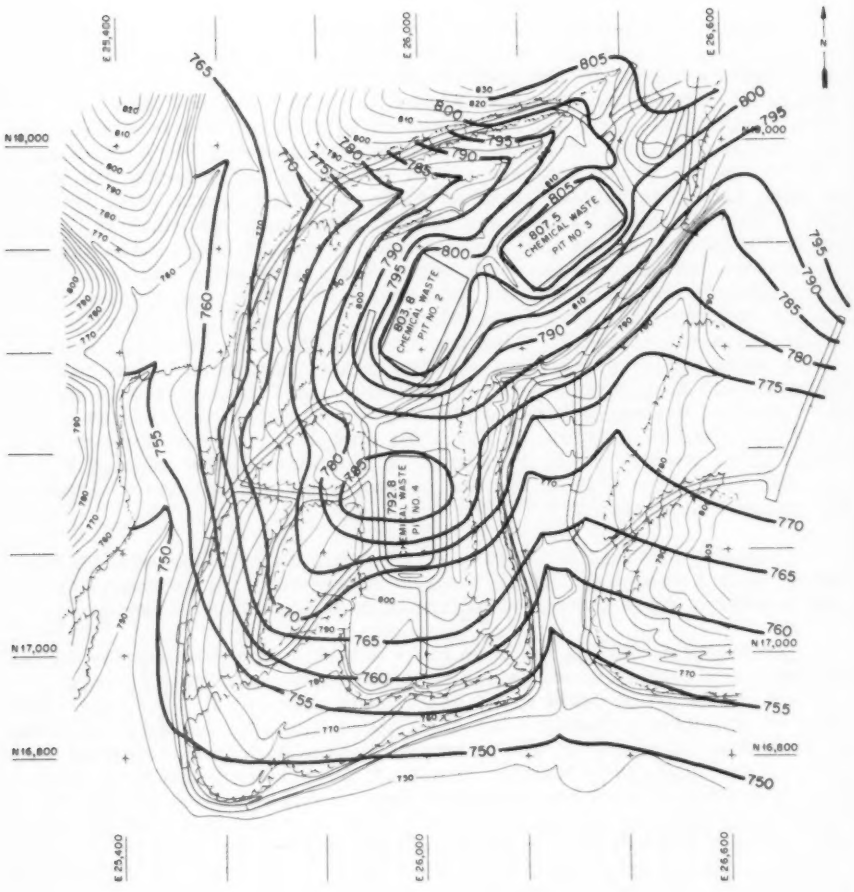

Figure 11. Water Table Map, January 10, 1958.

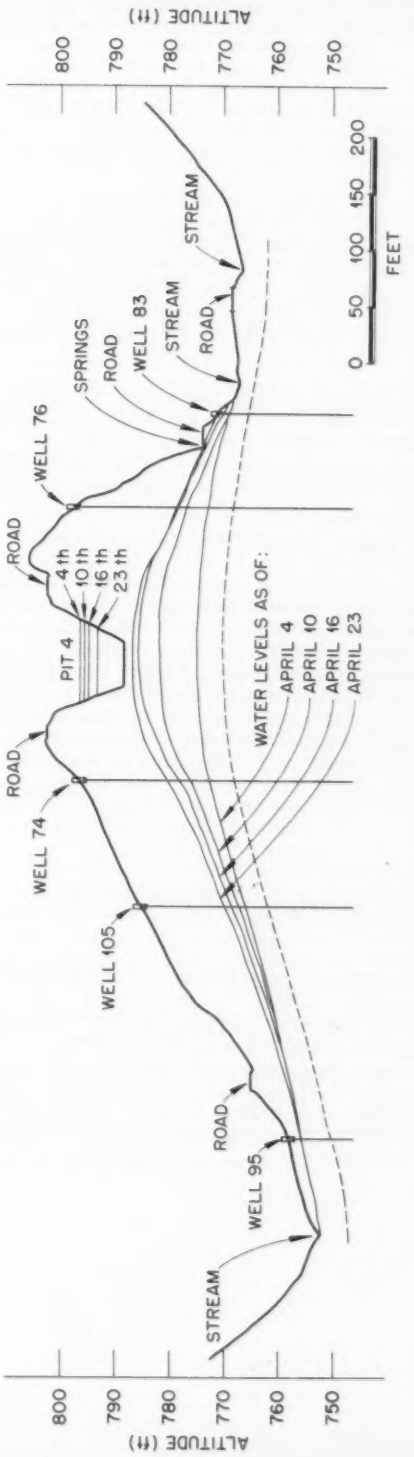

Figure 12. Cross Section, Pit 4.

Calculation of these values should not suggest that the hydrologic characteristics of the pits or of the shale around them are known. We do not know the thickness of weathered shale through which the waste is moving and 30 feet may be too large a value, particularly for points a little distance from the pits. We do not know the movement through the fresh shale below is quantitatively unimportant. Until these questions can be answered it will be impossible to determine the volume or the geometry of the ion exchange column represented by the shale around the pits.

Two small streams flow past the low ridge on which the three pits are located, one on the east, one on the west. The liquid that seeps out of the pits travels underground for distances of from 150 to 600 feet, then it seeps up through the beds of the streams and joins their flow. Some of the waste appears at the surface in the form of small surface seeps near the edges of the streams, and some, when Pit 4 has waste in it, appears in a line of active springs in the gutter of the road at the foot of the bank to the east of the pit.

None of the waste can move to the north from the pits, and none can pass the streams to the east and west. To the south the two streams drain into the former basin, at White Oak Lake, now dry, out of which the water flows through a weir and sampling point. The liquid escaping from the pits will not therefore inadvertenly become hazard even if details of its movement are unknown.

DISPERSION OF STABLE CHEMICAL WASTE CONSTITUENTS

Waste that has been pumped out to the pits has come from several different sources and during different periods, has been pretreated in a variety of ways. Before going to the pits most of the waste is neutralized and stored in tanks. Sludges, which are largely hydroxides and carbonates, form in the tanks and carry down with them most of the radioactive strontium, barium, and minor amounts of some of the other fission products. Some of the sludge is carried out to the pits with the liquid waste, and still more sludge appears to have formed in the pits. Because of the several orgins and complex history, there have been many variations in the composition of the waste going into the pits; Table 4 below gives the average concentration of the chemical ions in the waste which has gone into each of the three pits since July, 1954.

TABLE V

CHEMICAL COMPOSITION OF WASTE SENT TO PITS
(Values in Parts per Million)

Pit	Na	NH_4		NO_3	SO_4	Cl	OH	Total Solids
3	15,600	400	600	23,400	3,400	200	3,500	55,800
2	13,600	100	400	20,300	2,700	200	2,500	47,300
4	11,200	100	300	18,600	2,900	100	1,800	40,700

By July 1, 1957, a total of about 1,800,000 pounds of nitrate and 1,400,000 pounds of sodium had gone into the three pits. There is about a 10 per cent reduction in nitrate concentration from Pit 3 to Pit 2, and again from Pit 2 to Pit 4; this represents loss of nitrate by seepage into the shale and dilution by rainfall. The nitrate is not held in the soil and virtually all of it appears in the two small streams which flow into the Clinch River. The surface seep which is 600 feet west of Pit 2 contains about 1,800 ppm of NO_3, roughly a tenfold reduction in concentration of nitrate from that of the liquid in the pit. The springs 150 feet to the east of Pit 4 show an approximate two- to threefold reduction in nitrate concentration. The dilution factors vary with the season of the year and with the weather; this makes an exact inventory very difficult. If all the nitrate discharged to the pits reaches the Clinch River, the concentration in that stream, assuming complete mixing, would be 0.036 ppm, (nitrate, 360,000 lbs. per year; Clinch River flow, 5,000 cubic feet per second, or 10^{13} pounds per year). This is about 0.1 per cent of the maximum permissible concentration. The movement and dilution of the nitrate which is not adsorbed by the soil, may prove a valuable guide when more data are available, to what is happening to the radioactive constituents in the waste.

The sodium, like the nitrate, is reduced about 10 per cent in concentration by dilution as the waste moves from Pit 3 to Pit 2, and again from Pit 2 to Pit 4. However, in the 600-foot underground journey from Pit 2 to the surface seep to the west, the sodium concentration is reduced roughly 50 fold, as against a 10 fold reduction of the nitrate. The water in the seep, however, has much more calcium in it than the normal ground water; sodium is apparently being taken up by the shale in exchange for calcium. The possibility that the steep bank which forms the east side of Pit 4 (see Figure 12) might collapse if the pit were nearly full at the time of a heavy rain, has long been recognized even though the bedding in the shale is at right angles to the direction of potential movement. The substitution of sodium for calcium may well weaken the shale mechanically and the replacement reaction is therefore of some interest.

WELL LOGGING AND SAMPLING

Movement of active material out from the pits in the escaping liquid has been followed by well logging and sampling in some fifty observation wells in the area and by the analysis of samples taken from surface seeps and streams. The well-logging units in use are of two general types. The first is a trailer-mounted count rate meter to which is attached a long cable and a water-tight aluminum casing containing a halogen-type GM tube and a preamplifier. The second type of unit is similar but employs scintillation detectors. The GM equipped units are more satisfactory for field use than the scintillation type units particularly in wells in which the activity is fairly high. Although both types of instruments have been calibrated in air and in simulated "wells" made of short sections of pipe inserted in barrels filled with measured amounts of radioactive solution, it has not been possible to convert instrument response at all points in a well into specific activity.[8] The parameters

which determine instrument response at any point include: concentration of activity in solution, well diameter, active material adsorbed on the walls of the well, and active material in fractures extending back into the rock. It is seldom possible to separate these several factors. Nevertheless, the well logging is of great value in detecting the arrival of activity in a well and in locating the first points of entry; later the whole well tends to become radioactive, and the record is blurred. The well logging is also of varue in indicating the places in a well at which samples shoudd be taken. The map shown in Figure 13 is based on the results of our sampling.

Despite the care taken with the well sampling and with the analysis of the samples, the locations of the wells themselves had to be chosen arbitrarily and they may not intersect the channels of highest waste concentration. The wells are cased down to firm shale, therefore the samples do not necessarily represent the liquid in the weathered shale which is the important zone of flow. Pumping the monitoring wells, although perhaps desirable in theory, is hardly practical, and in any case would introduce still other complexities which would be difficult to evaluate.

The level of activity in the wells around Pits 2 and 3 has been approximately constant for some time, although it is anticipated that eventually the concentrations of the radionuclides will increase. The level of activity in the observation wells around Pit 4 fluctuates in response to the amount of waste in the pit and to the rate at which the pit is leaking. The lag in this response, as well as the time required for activity to reach the well after the pit was first filled, gives a measure of the rate of movement of waste out from the pit.

Logging in a sealed hole below Pit 4, made by grouting a string of tubing into the central well used in the pumping test, shows that the waste had thoroughly penetrated the shale to a depth of 6 feet below the bottom of the pit within approximately 4 weeks after the first waste was added, and that some 8 weeks later it had reached down as far as 20 feet, to the bottom of the weathered zone. Locally, in some of the observation wells, there is evidence of waste moving in fractures in fresh shale down to a depth of 60 feet and in one well perhaps even to 200 feet, but this is exceptional and quantitatively unimportant. The bulk of the waste, as anticipated, is moving through the weathered shale, and in particular through a zone a few feet thick lying directly on top of the unweathered rock. Not infrequently the first appearance of activity in a well is at the water table.

DISPERSION OF RADIOACTIVE WASTE CONSTITUENTS

The concentration of radionuclides in the waste, like the concentration of stable chemical constituents, varies from time to time with changes in operation. Table VI below shows the radioactive nuclides in a sample of the waste transferred from Pit 3 to Pit 2 on October 19, 1956.[6] The waste pumped into Pit 3 has a somewhat higher activity, but the values shown will serve as an illustration.

TABLE VI

RADIONUCLIDES IN WASTE, TRANSFER PIT 3 TO PIT 2, OCTOBER 19, 1956

Radionuclides	Micro-Microcuries per ml (μμc/ml)
Cesium 137	660,000
Ruthenium 106	94,000
Niobium 95	13,000
Strontium 89 and 90	7,000
Cobalt 60	7,000
Rare Earths and Yttrium 90	7,000
Antimony 125	4,000
Zirconium 95	1,000

As the waste moves from Pit 3 to Pit 2 there is a reduction of about threefold in total activity, and approximately the same reduction between Pit 2 and Pit 4 - far too much in each case to be accounted for by dilution. During storage in the pits active material is lost by decay, precipitation and adsorption on the shale walls.

Waste is moving out laterally from Pits 2 and 3 along the strike at a rate of about 2 to 6 feet a day. Movement from Pit 3 has been largely to the east from the north end of the pit towards the seep marked I on Figure 13. In all probability a similar tongue of waste is moving to the east from Pit 2, or 3, to form the surface seep marked II, but if so it has not been picked up by the monitoring wells. The principal movement out of Pit 2 is to the southwest, in a direction somewhat across the strike, suggesting that there are unknown structural or other geologic factors in this area which determine the direction of movement of the waste, or that our present network of observation wells and methods of well logging and sampling do not give a complete and accurate picture of the movement of the waste underground.

Waste moves east and west from Pit 4 at a rate of 10 to 30 feet a day and appears in the springs along the road at the foot of the ridge in ten days to two weeks. It was anticipated that Pit 4 would leak rapidly to the east and that springs would form. The site was accepted because it would permit the new pit to take overflow from Pits 2 and 3, and because the amount of activity involved does not represent a hazard sufficiently great to require the higher cost of the new wells and pipeline necessary to develop a new area.

Very little activity, however, has moved south from Pit 4. The south observation well (No. 75) which showed a large change in water level during the pumping test in the area, is only some 30 feet south

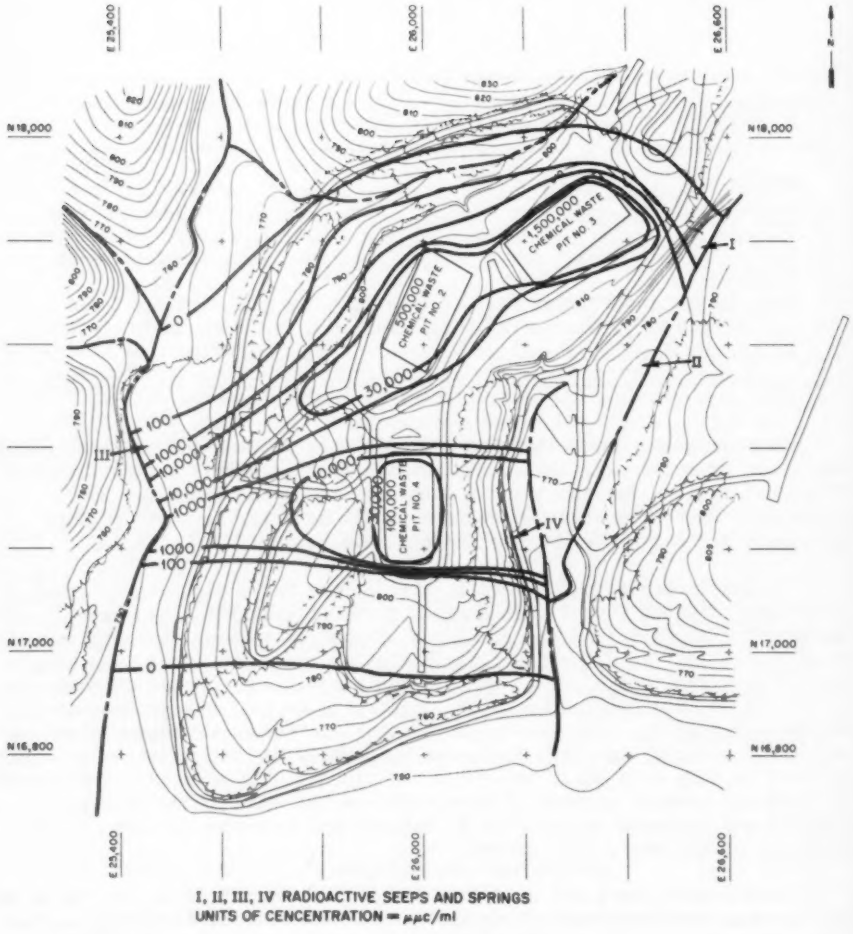

Figure 13. Distribution of Activity; Febuary 1958.

of the end of the pit. The records are incomplete, but apparently about a year elapsed before activity reached this well, and the concentration is still very low. The activity has appeared at a depth of 50 feet, just below the water table, but not at 110 feet where pressure testing had found a fracture. This corroborates some of the conclusions from the pumping test, namely, that movement from or to this well would be impeded by a hydraulic barrier immediately to the south of it, and that when there was movement it would be at 50-foot, not at the 110-foot level. Other questions need to be answered. For example, well No. 93, some 150 feet south of Pit 4, had activity in it only a little over a month after waste was first run into the pit. How it got there, without being found also in in well no. 75, we do not know.

In a general way the waste appears to be moving out of the pit as anticipated, namely, through the weathered shale in a direction parallel to the bedding. Although the expense and time required for the present monitoring program is a major part of the cost of the disposal operation we have been unable to explore in detail the pattern of movement of the liquid waste and of its several chemical and radioactive components.

LABORATORY STUDIES

The adsorptive capacity of Conasauga shale has been investigated by several groups in the laboratory. The ion exchange capacity of the weathered shale ranges from about 6 to 12 milliequivalents per 100 grams; a value of 28.6 meg/100 g has been reported for one sample.[7] Passing waste through shale packed in glass columns shows that the first active material to get through is the ruthenium; indeed, in one experiment about 80 per cent of the ruthenium passed through the shale without being delayed at all; the other 20 per cent was firmly held.[9] Ruthenium, like other members of the transition series, exhibits a very strong tendency to form complex ions; there is no evidence that any simple ions of ruthenium ever exist in water solutions. The ability of the larger part of the ruthenium to move through shale in a laboratory column is in agreement with field observations; ruthenium 106 is the only radionuclide that has been positively identified in important amounts in any of the observation wells or seeps, although a few samples have been found containing traces of radioactive cobalt and antimony. We are certain, however, that the sampling program does not give a complete account of what is happening.

There are some important unresolved problems about the adsorption of ruthenium. The 80 per cent which passes through a shale column presumably represents that fraction which is anionic or in a nonionic complex; the 20 per cent adsorbed is presumably cationic. This proportion depends on the other ions present, so the efficiency of rutheium removal may be subject to some control by altering the chemical composition of the waste solutions. An equilibrium probably exists in any waste solution between the cationic, anionic, and complexed ruthenium. With the cationic form removed, some of the anionic or complexed ruthenium may slowly alter to the cationic form. The complex factors which control the rate of this adjustment are not known, but Blanchard, Kahn, and Robeck[6] found that there is some continuing removal of ruthenium as long as the

waste remains in contact with the shale. At present some 2000 to 3000 curies of ruthenium a year are discharged into the pits. If only 20 per cent were removed by the shale, some 1600 to 2400 curies would escape. Sampling of White Oak Creek, which drains the pit area, suggests that only about 23 curies of ruthenium a year is actually escaping. Because the mechanism of the reactions responsible is not understood, one cannot predict how long this favorable relation will last, or plan for it in the location and design of future pits.

The removal by adsorption of the other fission products in the waste is very much more complete: data from one experiment show cesium 99.991 per cent, trivalent rare earths 77 per cent, and strontium 98.6 per cent. At first glance, the ability of the shale (in the laboratory) to hold only 20 per cent of the ruthenium suggests that the over-all decontamination factor of the pit system, in terms of gross beta activity, is a little less than 10. But as Table VII shows, if one takes into consideration, as one must, the MPC values of the several nuclides, the advantage gained from the use of the pits is actually very substantial. The column experiments suggest a reduction of about 100 in the dilution that would be required to meet drinking water standards; measurements in White Oak Creek suggest that the hazard reduction obtained in actual operation is even larger, although better data will be necessary to prove this.

Small amounts of cobalt 60 and antimony 125 which are present in the waste also form complexes and move through the shale in the laboratory columns. They are apparently doing the same in the field. In the laboratory, the next radionuclide after ruthenium to appear in the effluent is cesium 137. Its arrival does not represent saturation of the column, but the timing is even more important, for when cesium 137 appears in the surface seeps and streams below a pit in more than trace amounts it will be time to take that pit out of service. To judge from laboratory observations it should be possible to run 100,000 gallons of waste through one cubic yard of shale before there is a significant increase in the amount of cesium in the effluent. This figure cannot be used to predict the life expentancy of the pits. In the first place, the shale used in the

TABLE VII

REDUCTION IN DILUTION REQUIREMENT ON PASSING WASTE THROUGH SHALE-FILLED COLUMN

	MPC* μc/ml	Column Influent Concentration μc/ml	Dilution Required	Column Effluent Concentration μc/ml	Dilution Required
Cs^{137} + Ba^{137}	4.5×10^{-4}	$6{,}600 \times 10^{-4}$	1,470	$.624 \times 10^{-4}$	None
Sr^{90} + Y^{90}	2.2×10^{-7}	$70{,}000 \times 10^{-7}$	31,800	960×10^{-9}	440
Ru^{106} + Rh^{106}	1.4×10^{-2}	9.4×10^{-2}	6.7	8.45×10^{-2}	6
			33,276.7		446

*Recommendations of the International Commission on Radiological Protection. To be published in 1958.

laboratory is crushed and sieved, so that there is excellent contact between shale and waste; this is hardly true in the field. Secondly, the concern in the field is with possible movement along exceptional routes; through-going fracture systems with small surface area and low adsorption. However, because it is known that the appearance of cesium is critical, it has been possible to direct monitoring in the wells and streams towards an early identification of that nuclide. Studies of vegetation growing in the contaminated areas near the pits have revealed some cesium in leaves and stems, and also in the litter on the ground. There is no evidence that growing vegetation will concentrate cesium,although this is possible in a potassium-poor soil, such as is found in the pit area. The cesium may not come from the pits, or if it does it may move on dust carried from the sides of the pits. Air filters near the pits detect some airborne activity but the amount is small and does not at present constitute a hazard.

FUTURE PIT DEVELOPMENT

As a result of these studies it is believed possible to build pits which will be better than those now in use. The site for the next pit has been chosen on a ridge just to the east of Pit 4. The depth to ground water here is about 40 feet, nearly what it was at the Pit 4 site, so that the leakage rates should be rapid enough for economical operation. This ridge is wider than the Pit 4 ridge, and there will probably be no active springs, although surface seeps may develop near the streams. The pit will probably be 300 feet long, 25 feet wide at the top, 15 feet deep, and with sides that slope in so that the width of the bottom will be negligible. The present pits leak almost entirely through their sides. The pit will be orientated at right angles to the strike to intercept the maximum number of bedding planes. In this way the escaping liquid will move through, and come in contact with, the largest volume possible of shale. Because a reduction in the storage capacity of the pit is not a disadvantage, the pit will be filled with coarse crushed rock, and a mound of dirt compacted over it. This should not affect the seepage rate very much, but the effects of both rainfall and evaporation will be eliminated,-- a net gain in itself, and a great aid in establishing the pit inventory. The potential danger of airborne contamination will be eliminated and the radiation hazard for those making studies of the pit operation will be very greatly reduced. If a critical situation developed near the present pits, it would be nearly impossible to conduct a thorough investigation or to take remedial measures. Although the first cost of a rock-filled covered pit would be somewhat higher, the final cost might well be less. When the present pits are abandoned they will have to be filled in, if only to cut down on the radiation field and the potential dust hazard. This will be expensive, because the work will have to be done under very restrictive working conditions. The proposed new pit could be abandoned simply by turning a value. The design of the first pit built at Oak Ridge placed much emphasis on waste storage, the design and location of the next three pits appear to give joint recognition to the need for both storage and ion exchange. The fifth pit, when it is built, will be designed solely as an ion exchange device,

CONCLUSIONS

The waste disposal pits at Oak Ridge have been operating for about seven years, and have handled with apparent safety many millions of gallons of radioactive waste. There is some concern, however, about their future. Although rather simple changes in location and design can probably correct some of the more obvious defects of the present system, it is unlikely that it will ever be possible to determine in as much detail as desirable the movement of the radioactive materials away from pits of any type. In an area of more homogeneous rocks and simpler structure, it would be possible to learn more, but it does not appear that such a device can ever be operated safely near important centers of population if it is required to handle substantial amounts of radioactive materials. Disposal pits can serve a useful purpose, as they have at Oak Ridge, as a temporary measure to handle limited amounts of waste while better methods are being developed. The better methods may also involve the fixation of radioactive strontium and cesium on clay, but the operation would be conducted under conditions which would permit a more thorough understanding and provide better control.

BIBLIOGRAPHY

1. Struxness, E. G., Morton, R. J., and Straub, C. P., Disposal of Radioactive Wastes into Terrestrial Pits, Peaceful Uses of Atomic Energy, Paper 140, Vol. 9, p. 684, New York, (1956).

2. The Disposal of Radioactive Waste on Land, report of the Committee on Waste Disposal of the Division of Earth Sciences. National Academy of Sciences - National Research Council, Publication 519, April, (1957).

3. Langbein, W. B., Hains, C. H., and Culler, R. C., Hydrology of Stock-Water Reservoirs in Arizona - Progress Report. U. S. Geological Survey Circular 110, Washington, D. C., (1951).

4. Kohler, M. A., Nordenson, T. J., and Fox, W. E., Evaporation from Pans and Lakes, U. S. Weather Bureau Research Paper No. 38, May, (1955).

5. Richardson, R. M., Tidal Fluctuations of Water Level Observed in Wells in East Tennessee. Amer. Geophysical Union. Transactions, Vol. 37, No. 4, pp. 461-462, (1956).

6. Blanchard, R. L., Kahn, B., Robeck, G. G., Laboratory Studies on the Ground Disposal of ORNL Intermediate-Level Liquid Radioactive Waste, ORNL Report 2475, March, (1958).

7. Unpublished results of U. S. Geological Survey.

8. Cowser, K. E., and Parker, F. L., Soil Disposal of Radioactive Wastes at ORNL. Criteria and Techniques of Site Selection and Monitoring, Health Physics, Vol. 1, No. 1, (1958).

9. Lacy, W. J., Radioactive Waste Disposal Report on Seepage Pit Liquid Waste-Shale Column Experiment. ORNL Reporr No. 2415, Nov., (1957).

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EXPERIENCE IN THE DISPOSAL OF RADIOACTIVE WASTES TO THE GROUND

By

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INTRODUCTION

Disposal of low level liquid radioactive wastes to the ground at the Hanford Works, Washington, the Oak Ridge National Laboratory, Tennessee, and the Savannah River Plant, South Carolina, is founded on the ability of various earth materials to remove and retain fission product cations.

Twelve years of practical experience in the controlled disposal of wastes to the ground at the Hanford Works, seven years at the Oak Ridge National Laboratory, and four at the Savannah River Plant, have demonstrated the feasibility, safety, and economy in the disposal of at least limited volumes of some types of liquid wastes at shallow depths.

Previous reports (1, 2, 3, 4, 5, 6, 7) summarize work at all three sites to late 1955. The present paper describes more intensively some of the experience which indicates the potential of this disposal method and the problems involved.

The disposal experience is summarized in Table 1 which shows total gross

*Hanford Laboratories Operation
Hanford Atomic Products Operation
General Electric Company
Richland, Washington

**Oak Ridge National Laboratory
Union Carbide Corporation
Oak Ridge, Tennessee

***Savannah River Plant
E. I. duPont de Nemours & Company, Inc.
Wilmington, Delaware

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beta-emitter activity and cumulative volumes at the three sites. It is apparent that the average activity at Savannah River is the lowest and that at Oak Ridge the highest; see also (8).

TABLE 1

COMPARISON OF THE THREE MAJOR PRODUCTION SITES

	Cumulative Total Volume liters	Cumulative Total Gross Beta-Emitter Activity curies
Savannah River	5.0×10^8	2.4×10^2 *
Oak Ridge	2.6×10^7	1.0×10^5
Hanford	1.2×10^{10}	2.4×10^6

*Not including 2300 curies of I^{131}

In addition to the 1.2×10^{10} liters of radioactive wastes discharged to ground, Hanford has also discharged more than 1.0×10^{11} liters of normally uncontaminated process cooling water to open swamps. The Hanford problem is one of management of large volumes of water as well as the control of the radioactivity.

Within the limit of present experience and knowledge, demonstrable hazards have not developed at any of the three sites.

GEOLOGIC AND ENVIRONMENTAL SETTING

The three sites lie in markedly different settings. Hanford lies in the south-central part of Washington in a semi-arid region in the rain-shadow of the Cascade Mountains. The annual rainfall is low (17 cm) and the water table lies deep (175-320 m). Oak Ridge National Laboratory and the Savannah River Plant lie in humid regions, the first in the southern Appalachian Mountains of Tennessee, the second on the southern Atlantic Coastal Plain of South Carolina. The rainfall is respectively about 132 and 110 cm, the water tables lie correspondingly at depths up to 15 m and from 10-20 m deep. At all three sites the water table discharges into surface streams within the plant boundaries; these are (1) White Oak Creek, 60 to 120 m from the Oak Ridge disposal sites; (2) the Savannah River, about 10 km from the Savannah River sites; and (3) the Columbia River, 8 to 32 km from the Hanford disposal locations.

The formations into which the wastes are discharged and through which they move are sedimentary rocks at all three sites - folded, jointed, locally weathered, ancient Paleozoic sandstones, siltstones, weathered shales, and limestones at Oak Ridge; late Mesozoic to middle Cenozoic

marine sands, clays, limestones and local gravels at the Savannah River site; and latest Cenozoic (Pleistocene) to recent lake and stream-deposited calcareous sands, silts, gravels, and clays, with sandy gravels predominating, at Hanford.

Significantly the clay minerals at Savannah River are largely kaolinites with a low exchange capacity, whereas those at Oak Ridge and at Hanford are largely montmorillonites with correspondingly high exchange capacities.

HANFORD EXPERIENCE

Disposal to the ground of small volumes of selected, very low level waste from Separations Plant processes began at Hanford late in 1945. The appreciable distances to the Columbia River originally suggested that the hazards in such disposal were probably minimal for those wastes. Preliminary studies moreover indicated that all the ground waters moved from the hills enclosing the Pasco Basin beneath the project and into the Columbia River, hence entirely below land under the control of the Atomic Energy Commission. The potential for appreciable ion exchange was also recognized as was dilution in the Columbia River of any liquid reaching it. Extensive well drilling, beginning early in 1947, disclosed that the limited disposal was adequately safe, hence disposal of somewhat greater volumes followed under close control and with increasing research effort in the appropriate physical sciences. Hanford's waste program is today supported between a closely correlated and balanced program of theoretical study, laboratory and field experiment, and observational experience.

Disposal of liquid wastes to the ground at Hanford is permitted until biologically significant isotopes with a half life of three years or greater are detected in the ground waters at the disposal site in concentrations up to 1/10 of the N.C.R.P. limits. Contamination of the ground waters by significant amounts of Ru^{106}, Ru^{103} and U is thus permitted and indeed the first of these isotopes serves as a useful leading or indicating cation in the ground waters (1).

The four types of disposal facilities used at Hanford may be recalled (1). These are reverse wells, cribs and caverns, trenches, and swamps.

(1) Reverse wells were used to a limited extent early in Hanford history for some low-level wastes. They proved unsatisfactory owing to the ease with which they became plugged; moreover they introduced the wastes into the ground close to the water table, denied use of the long earth column above the water table, and were difficult to monitor. Reverse wells are now used mostly for laboratory wastes of low volume.

(2) Cribs are large boxes open on the bottom only and buried at depths great enough to preclude radiation problems at the ground surface. Cribs provide a surge capacity and spread the waste liquids over the sediments.

Additionally they serve more nearly as a point source, rather than as a line or area source hence monitoring of the solutions is easier and the crib life is more predictable. Caverns are cribs without the timber structure, with the excavation filled with sorted gravel to provide surge capacity particularly for larger volume streams. Cribs and caverns are monitored by up to 9 wells drilled within a 8-10 m radius of the crib center prior to its use, and by additional wells at greater distances in the indicated direction of movement of the wastes. The behavior of the wastes is determined from sediment and water samples obtained from the bottoms of wells ending above the water table; from water samples from wells ending beneath the water table; and by means of radiation detection probes and other special in-well instrumentation. Crib sites are redrilled when deemed necessary to determine the extent and distribution of the various radioisotopes but generally the small quantity of radioisotopes leaving a site is of primary concern and is monitored rather than sampling and assaying the large mass remaining behind.

Some examples of experience with disposal to cribs will be described.

Laboratory experiments with a low activity, high salt waste (0.1 uc of fission product beta emitters per cc and 80 g/l total salts) showed that Ru^{106} would be the leading radioisotope and would be followed by Cs^{137}. Sediment samples routinely taken during a 6 year period from an open-bottom cased well passing directly through a crib receiving this waste and bottoming 6 meters beneath it showed a steady rise in total beta activity and a significant cesium content. A well about 30 m from the crib was studied in detail. The well was seated in a bed of silt and clay at a depth of about 25 m and was perforated above that level to permit the entry and passage of waste liquids as they moved across the surface of the bed in their path to the regional water table about 35 m deeper. Previous studies of the ground water in the area indicated that the wastes would move toward and past the well from the crib. Sediment and liquid samples obtained from the bottom of the well showed more than 95% Ru^{106} and ca. 5% Cs^{137}. Because the original waste contained about 40-45% Ru^{106} and the same percentage of Cs^{137}, the interpretation was that Cs had been removed upstream but that Ru had penetrated more deeply. Sediment and liquid samples from the shallow well showed an increase with time in the Cs:Ru ratio and this, together with the increasing Ru^{106} concentration in the ground water, permitted estimates to be made of the progress of the Cs front and resulted in the recommendation that the crib be abandoned. This was done after 10^8 liters containing 3000 curies of beta emitters had gone to ground there. Continued sampling of the ground waters at the site ultimately disclosed the presence of trace amounts of Cs^{137} in the water, significantly below 2×10^{-3} uc/cc, and validating the predictions of its possible appearance.

A second site received large volumes of low-salt, low-level waste over

a 3-year period. Laboratory experiments with the actual wastes suggested the imminent breakthrough of detectable amounts of Sr^{90}. Twelve wells, in addition to the three already present around the crib, were drilled to determine the configuration and the levels of contamination. The crib was removed from service following the disposal of 1.5×10^8 liters of waste containing 753,000 curies of gross beta emitters. About a year subsequent to shut-down of the crib, traces of Sr^{90} were found in the ground waters in one well alongside the crib up to levels of about 1×10^{-6} uc/cc. It was concluded that the Sr appeared as the result of the drainage of the long soil column following crib shut-down. Although the 15 wells surrounding the crib have been sampled weekly to date, Sr^{90} has never been detected in other than the one well although Ru^{106} consistently has been found in down-gradient wells.

Early ion exchange studies of fission product behavior showed that Ru species were delayed only slightly in their movement through laboratory soil columns. In related field work, sampling of the ground waters in more than ten wells disclosed that nitrate ion travelled about 520 m from a disposal site in eight years, whereas the Ru^{106} from the same waste could be detected only at about 370 m in the same time. A time lead of the nitrate over Ru^{106} of about 30 months is indicated under the specific conditions of this observation. A correspondingly greater lead time of nitrate over Cs^{137} or Sr^{90} would be expected.

A total of more than 1,700,000 curies of gross beta-emitters in about 1.8×10^{10} liters of waste has been discharged to ground at Hanford through a total of 70 cribs. No evidence has been obtained of long lived radioisotopes in the ground water at a distance of more than 350 meters from the disposal point; Cs^{137} was detected in a well at that distance at a concentration of 1×10^{-6} uc/cc and Co^{60} at 1×10^{-5} uc/cc.

(3) Trenches are once-used ground disposal facilities. Isolated batches of waste that may interfere with ground exchange reactions at other disposal sites or wastes with exchange capabilities disallowing disposal to cribs have been discharged to trenches under demanding conditions. Here the disposal is based on the moisture-retaining or specific retention property of the dry sediments above the water table. No allowance is permitted for exchange reactions which undoubtedly occur. Currently only the vertical earth column beneath a trench is considered to be available and no lateral spreading is assumed. Originally 10% of the column volume was assumed for useful specific retention. Recent laboratory studies and calculations have indicated an average effective retention of about 6% and this figure is now used.

In a case of trench disposal, about 1.5×10^7 liters of high salt waste were discharged to a total of eight trenches in one site beginning late in 1953 and extending through 1954. Included in these wastes were a recorded 15,790 curies of gross beta emitters, 5.66 g Pu, 102,550 g U, 6866 c Cs, 3206 c Sr, and 213 c Sb. Little Ru was present

in these aged wastes, the remainder of the radioisotopes being largely rare earths. Three wells drilled to basalt, less than 7 meters beneath the water table at the site, and around the trench system have to date shown detectable amounts of only Ru, U and several non-radioactive salts and these contaminants are present in concentrations that increase toward several nearby crib sites and are more probably derived from those sites where large quantities of Ru as well as U and non-radioactive salts were sent to ground.

A total of more than 640,000 curies of gross beta-emitters in more than 10^8 liters of waste has been discharged to ground at Hanford through a total of 18 trenches. No evidence of ground water contamination with radioisotopes coming from these specific retention sites has been found.

(4) Swamps are natural depressions into which essentially uncontaminated process cooling waters are discharged. The presently permitted level of contamination of water going to a swamp is less than 5×10^{-5} uc of mixed beta emitters per cc, which level does not result in appreciable contamination beyond the confines of the swamp, nor in radiation dose levels as the result of concentration on mud or vegetation.

Two mounds have been formed by the discharge of water to the swamps (Figure 1). The westernmost of the two is nearly circular in plan reflecting the essential homogeneity of the sediments in which it lies. The easternmost mound is decidedly elongated north and south. Eastward movement of the ground waters there is inhibited by eastward dipping beds of silt and clay which rise above the water table and cause a preferential flow to the north and south.

Total water discharged to swamps feeding the easternmost mound has been about 3.1×10^{10} liters, and to the westernmost 7.2×10^{10} liters. Included in these volumes have been about 2000 curies of fission products and 130 grams of plutonium resulting from inadvertent contaminations.

While the swamps are regarded as sites for the disposal of water rather than of radioactive liquids, the resulting mounds have important effects on the rate and direction of movement of all ground waters. Mobile radioisotopes in water drained from disposal sites may therefore be redirected. It is a policy, however, not to establish purposely for the control of radioactive solutions an artificial ground water mound situation which it may be impossible to maintain indefinitely. Since swamp sites were chosen at the beginning of Hanford history and in keeping with plant locations, ground water management has taken an important place in the waste disposal picture.

In one case radioruthenium moved southeastward about 12 km from a disposal site on the western flank of the east mound, apparently in an ancient broad river channel. This followed an approximately 18 month period of negligible supply of cooling water to the swamp. Reactiva-

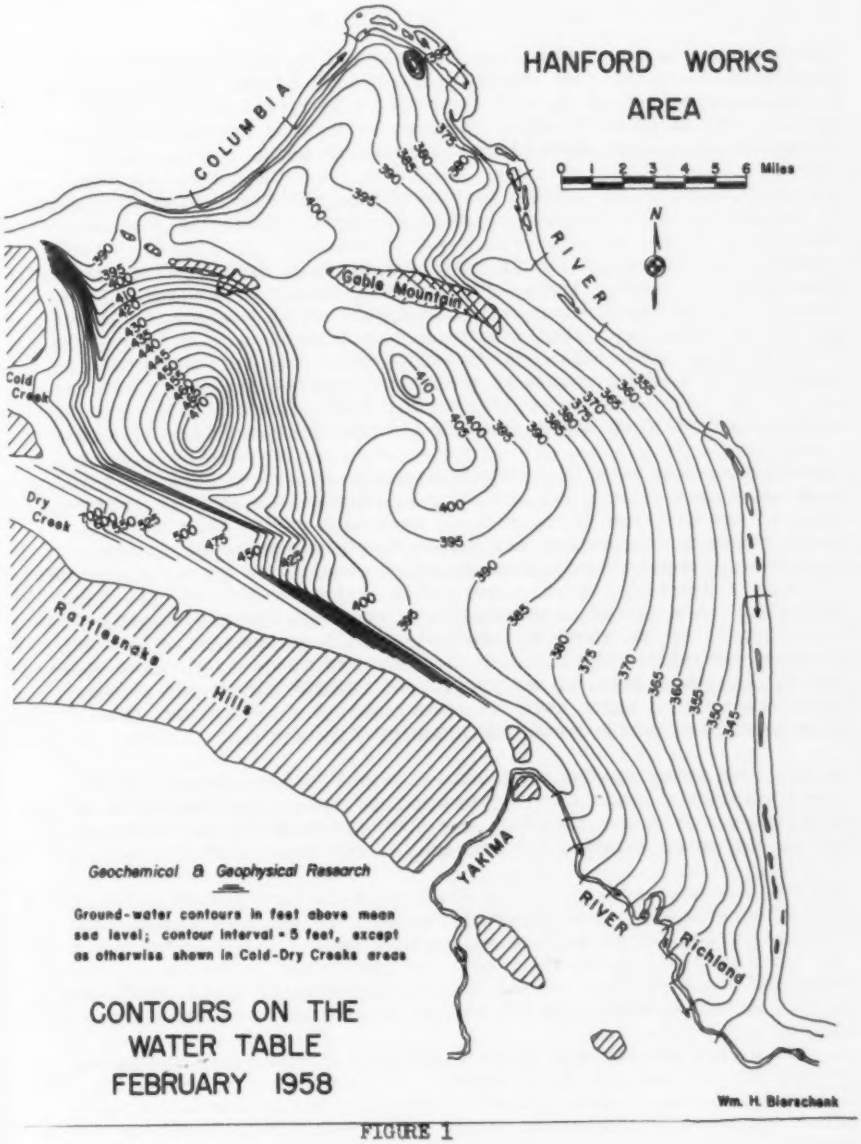


FIGURE 1

HANFORD WORKS AREA
CONTOURS ON THE WATER TABLE FEBRUARY 1958

tion of the plant and swamp area, establishment of a new swamp site to the north above more permeable strata, and division of the volumes disposed between the two locations terminated the southeastward flow of the contamination.

Rate of flow has been studied in this channel by tracer tests using fluorescein. In one case the dye was admitted to one well and detected in another over 1.2 km distant to which it travelled at an apparent average rate of 55 m per day. It appeared also in another well offset 30° and about equally distant in a comparable time.

All the preceding has implied the important part which wells have played in Hanford radioactive waste disposal practice. The wells have several functions: first, an exploratory one in obtaining geological, hydrological, and mineralogical information; secondly, in providing research facilities for pumping tests, tracer tests, and in-well studies; and finally, in the routine monitoring to supply water samples for detecting the activity level and movement of contamination. The wells have 20 cm diameter open bottom steel casings which may be unperforated or perforated at desired points or along the complete length. There are 575 wells of which 293 (total depth, 23550 m) are to the water table and 61 (6630 m) are to basalt; the remainder are dry (8710 m).

Work with uranium materials in one area near the river gave waste solutions which were discharged to seepage pits near the shore. Observations of the behavior of the uranium were made during rise and fall of the river by temperature and radioactivity measurements in the water in eighteen wells drilled around the basins and by river traverses and routine sampling. During the spring high water period (ca. 1.3×10^7 liters/sec river flow), contamination moved back from the basins under the influence of the reversed gradient as much as one-half kilometer although the water table gradient was affected up to about three kilometers. Decrease in river height (to ca. 2×10^6 liters/sec flow) moved detectable uranium back into the river at a point about one kilometer downstream from the recharge point.

In this same area, studies were made of the dilution obtained in the river. For the low winter flow, uranium concentrations decreased in one kilometer of river course to one five-hundredth of the concentration in the water entering the stream.

SAVANNAH RIVER PLANT EXPERIENCE

The Savannah River Plant is located in the Atlantic Coastal Plains. Ground water occurs in the uncemented sediments as perched water tables, normal water tables and in artesian aquifers. The normal water table depth below the ground surface is generally from 10 to 20 m. Rainfall is high with an average of about 125 cm per year. The clays are kaolinitic and have a low exchange capacity. These conditions do not appear to be satisfactory for ground disposal of high or intermediate level radioactive wastes and little such disposal has been made.

Open seepage basins are used for the disposal of low level high volume radioactive waste from the separations process. It would be economically unfeasible to evaporate the millions of liters involved in order to store the very small amount of radioactive material in underground tanks. Yet discharge of the waste to streams would be incompatible with the waste control philosophy of the plant which specifies that no radioactive material which can possibly be contained shall be released to the environment. The success of the seepage basins from this viewpoint has been demonstrated by the fact that only 0.1 curie of alpha emitters and 2.2 curies of nonvolatile beta emitters in liquid waste has reached flowing streams over several years.

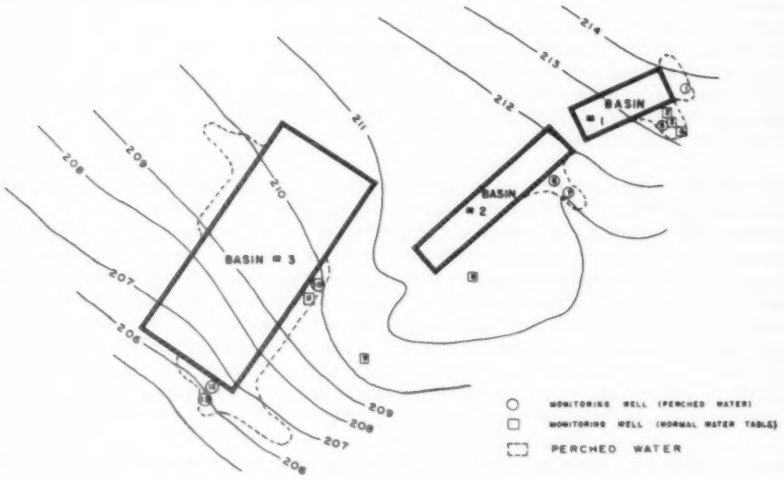
Each of the two process areas (F Area and H Area) has a series of three open seepage basins as shown in Figure 2. The total area of the six basins is 4400 m^2 and the depth of the basins ranges from 2 to 3 m. The basins were so designed that the overflow from basin one flows into basin two and the overflow from basin two flows into basin three. The first two basins in series are small compared to the third. This design was selected so that solids present or precipitates formed in the waste would settle in the first two basins leaving the third basin relatively free of solids and maintaining good seepage rates for a long period.

Up to December 1957 the volume of low level waste discharged to the basins has totaled 500 x 10^6 liters containing 2.5 curies of alpha emitters, 240 curies of nonvolatile beta emitters and 2,300 curies of I^{131}. The pH of the waste has varied from 2 to 11.

Ground water around the basins has been monitored by use of both permanent and temporary wells. A total of 25 steel-cased permanent monitoring wells was installed, 75 uncased temporary wells were drilled later to explore the extent of contamination. The permanent wells have been monitored routinely at intervals of from one to four weeks and the temporary wells were monitored when drilled and at intervals since.

Because of the geological differences between the seepage basins in each of the two process areas it is necessary to discuss the results of ground water monitoring separately for each area. In F Area there are two separate and distinct water tables underneath the seepage basins. One of these is a perched water table largely recharged by basin seepage which ranges from 3 to 8 m below the ground surface and extends up to

200-F AREA SEEPAGE BASINS
NORMAL GROUND WATER CONTOURS



200-H AREA SEEPAGE BASINS
GROUND WATER CONTOURS

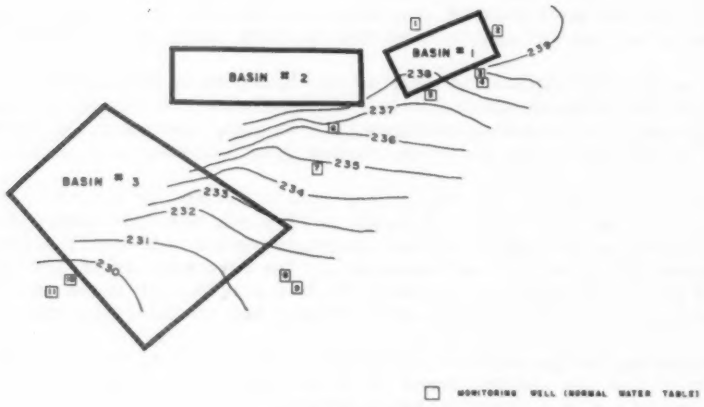


FIGURE 2

SAVANNAH RIVER PLANT SEEPAGE BASINS

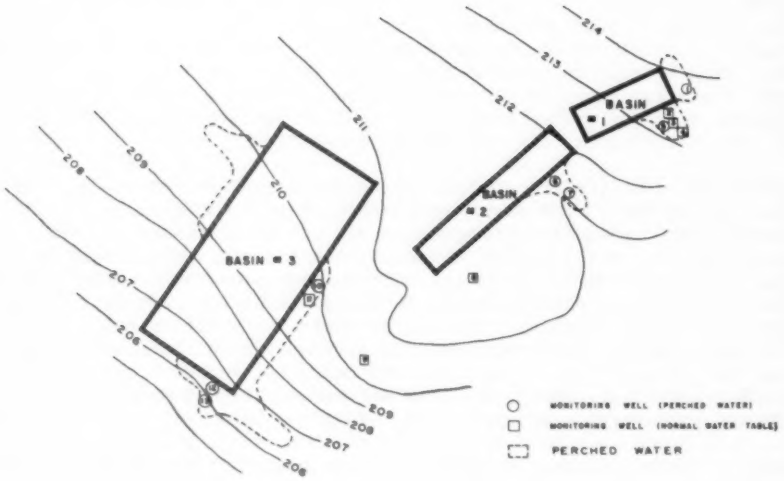
30 m from the seepage basins. The normal water table is approximately 20 m below the ground surface. The nearest surface outcrop of this normal water table is a flowing stream about 660 m from the basins. Seven of the permanent monitoring wells, as shown in Figure 2, terminate in the perched water. During the use of the seepage basins the concentration of both alpha and nonvolatile beta emitters has increased in the perched water at all well locations. The temporary wells showed that the concentrations decreased as the water moves out from the basins but that all of the perched water recharged by the basins is contaminated. At the outer extremity of the perched water, about 30 m from the basins, the concentration of alpha emitters was 8×10^{-3} d/m/ml and the concentration of nonvolatile beta emitters was 4.6×10^{-7} uc/ml.

Six of the F Area permanent monitoring wells, as shown in Figure 2, are located in the normal water table which is approximately 20 m below the ground surface. Water from at least two wells (wells 2 and 11) has contained detectable radioactivity from seepage basins. However, contamination of the natural water table does not appear to be increasing. In H Area the natural water table at the seepage basins is only 5 to 8 m below the ground surface and the nearest outcrop of the water table is a swampy area about 60 to 90 m from the basins. All 11 of the H Area permanent monitoring wells, as shown in Figure 2, are located in the normal water table. Contamination of the ground water around the H Area seepage basins appears extensive but quite variable. By far the highest concentrations of both alpha emitters and nonvolatile beta emitters have been in wells 1 and 5 and only in these two wells have significant concentrations of alpha emitters been detected. Although maximum concentrations of nonvolatile beta emitters in the remaining nine wells have been generally low (about 1×10^{-7} uc/ml) they all appear to have contained nonvolatile beta activity from the basins.

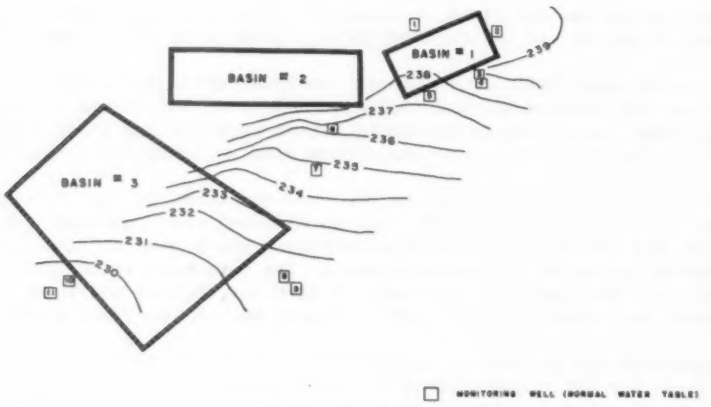
The presence of cracks or fissures in the H Area basin appears to be the primary reason for the very high concentrations in the permanent monitoring wells 1 and 5. Extensive drilling of the temporary wells located a narrow band of water at a distance of about 30 m from the first basin which contained 1.3×10^{-1} d/m/ml alpha and 2.0×10^{-7} uc/ml nonvolatile beta. Sodium ions added as NaOH at infrequent intervals apparently reduced seepage through the cracks or fissures and resulted in a decreased concentration of both alpha and nonvolatile beta emitters in the water from these wells.

Specific analyses have indicated that except for plutonium none of the radioactive isotopes are completely adsorbed by the soil. Iodine has been detected in all wells containing radioactive materials. The nonvolatile beta emitters which are detected in the ground water include ruthenium, zirconium-niobium, strontium-yttrium and rare earth isotopes. Uranium is the only alpha emitter that has been detected in the ground water.

200-F AREA SEEPAGE BASINS
NORMAL GROUND WATER CONTOURS



200-H AREA SEEPAGE BASINS
GROUND WATER CONTOURS



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SAVANNAH RIVER PLANT SEEPAGE BASINS

30 m from the seepage basins. The normal water table is approximately 20 m below the ground surface. The nearest surface outcrop of this normal water table is a flowing stream about 660 m from the basins. Seven of the permanent monitoring wells, as shown in Figure 2, terminate in the perched water. During the use of the seepage basins the concentration of both alpha and nonvolatile beta emitters has increased in the perched water at all well locations. The temporary wells showed that the concentrations decreased as the water moves out from the basins but that all of the perched water recharged by the basins is contaminated. At the outer extremity of the perched water, about 30 m from the basins, the concentration of alpha emitters was 8×10^{-3} d/m/ml and the concentration of nonvolatile beta emitters was 4.6×10^{-7} uc/ml.

Six of the F Area permanent monitoring wells, as shown in Figure 2, are located in the normal water table which is approximately 20 m below the ground surface. Water from at least two wells (wells 2 and 4) has contained detectable radioactivity from seepage basins. However, contamination of the natural water table does not appear to be increasing. In H Area the natural water table at the seepage basins is only 5 to 8 m below the ground surface and the nearest outcrop of the water table is a swampy area about 60 to 90 m from the basins. All 11 of the H Area permanent monitoring wells, as shown in Figure 2, are located in the normal water table. Contamination of the ground water around the H Area seepage basins appears extensive but quite variable. By far the highest concentrations of both alpha emitters and nonvolatile beta emitters have been in wells 1 and 5 and only in these two wells have significant concentrations of alpha emitters been detected. Although maximum concentrations of nonvolatile beta emitters in the remaining nine wells have been generally low (about 1×10^{-7} uc/ml) they all appear to have contained nonvolatile beta activity from the basins.

The presence of cracks or fissures in the H Area basin appears to be the primary reason for the very high concentrations in the permanent monitoring wells 1 and 5. Extensive drilling of the temporary wells located a narrow band of water at a distance of about 30 m from the first basin which contained 1.3×10^{-1} d/m/ml alpha and 2.0×10^{-7} uc/ml nonvolatile beta. Sodium ions added as NaOH at infrequent intervals apparently reduced seepage through the cracks or fissures and resulted in a decreased concentration of both alpha and nonvolatile beta emitters in the water from these wells.

Specific analyses have indicated that except for plutonium none of the radioactive isotopes are completely adsorbed by the soil. Iodine has been detected in all wells containing radioactive materials. The nonvolatile beta emitters which are detected in the ground water include ruthenium, zirconium-niobium, strontium-yttrium and rare earth isotopes. Uranium is the only alpha emitter that has been detected in the ground water.

Except for radioiodine, air-borne radioactivity near the open seepage basins has been negligible. A few particulates or droplets have been collected on verticle adhesive papers located about 3 m from the basin water. Yet the total air-borne alpha or nonvolatile beta emitters have been insufficient to produce detectable contamination on vegetation more than 3 m from the basin water. Evolution of gaseous radioiodine has been so rapid at times that the concentration in the air 8 m downwind from the basin has been as high as 8.5×10^{-8} uc/cc. Concentrations of radioiodine on vegetation as high as 3×10^{-2} uc/g has been observed at a distance of 50 m from the basins.

CONCLUSIONS

The problems associated with the disposal of high level radioactive wastes are certainly large and serious. However, the problems associated with the low to intermediate level streams, bulking many times the volume of Savannah River high level waste, are also of great importance. Even the essentially uncontaminated process cooling water cannot be released into many public waterways owing to its potentially significant radioisotope content. The experiences at Oak Ridge, Savannah River and Hanford point out means by which disposal may be accomplished but not without the assumption of an extensive and exhaustive research program and the grave responsibilities associated with that disposal.

1. Brown, R. E., Parker, H. M., and Smith, J. M., Disposal of Liquid Wastes to the Ground: Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, Aug. 8-20, 1955, Vol. 9, p/565.

2. Struxness, E. G., Morton, R. J., and Straub, C. P., Disposal of High Level Radioactive Wastes in Terrestrial Pits: Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, Aug. 8-20, 1955, Vol. 9, p/554.

3. Witkowski, E. J., Operating Experience in the Disposal of Radioactive Wastes in Open Pits: TID-7517 (pt. 1a), Oct. 1956, pp 105-115.

4. Clark, J. R. and Pohl, H. A., Earth Disposal of Radioactive Wastes at SRP: TID-7517 (pt. 1a), Oct. 1956, pp. 162-169.

5. McHenry, J. R., Rhodes, D. W., and Rowe, P. P., Chemical and Physical Reactions of (Hanford) Radioactive Liquid Wastes with Soils: TID-7517 (pt. 1a), Oct. 1956, pp. 170-190.

6. Brown, R. E. McConiga, M. W., and Rowe, P. P., Geological and Hydrological Aspects of the Disposal of Liquid Wastes: TID-7517 (pt. 1b) Oct. 1956, pp. 413-425.

7. de Laguna, W., Some Geologic Factors that Influence Disposal of Radioactive Wastes into Pits: TID-7517 (pt. 1b), Oct. 1956, pp. 426-456.

8. Division of Reactor Development, US Atomic Energy Commission, Status Report on Handling and Disposal of Radioactive Wastes in the AEC Programs: WASH 742, Aug. 1957.

AN INVESTIGATION OF THE DISPOSAL OF RADIOACTIVE WASTES INTO DEEP GEOLOGIC FORMATIONS

University of California, Berkeley
February 16, 1959

The two most commonly practiced methods of handling radioactive wastes are long-term storage in tanks and dispersal in the atmosphere or surface waters of the biosphere. In the case of high level liquid wastes tank storage, though relatively costly, appears to be the most suitable approach for some years in the future. On the other hand, many low level liquid wastes may be discharged into surface waters, perhaps with some preliminary treatment, and are thus adequately diluted to avoid hazard to health or economic loss to the water consumer. High level wastes may contain concentrations of fission products in the order of a kilocurie per gallon; low level wastes in the order of a microcurie per gallon. Between these extremes, which may differ by a factor of a billion or more in concentration, there are a great number of intermediate level wastes which represent too great a volume to simply store and too large an amount of radioactivity to be discharged directly to surface waters or even, in many instances, to the oceans.

There is no single or general solution to the problem of handling the intermediate level wastes. The nature of a particular waste, the environmental characteristics of the site at which it is produced, and the cost of various disposal alternatives are the major factors determining the choice of a disposal method. In many instances the disposal of a multimillion gallon per day flow of an intermediate or low level waste may constitute a more serious problem than the storage of a few hundred gallons per day of high level waste. This situation now exists in several European countries, where high population densities preclude the existence of remote or isolated sites.

Methods of handling large volumes of slightly radioactive solutions are somewhat limited. By chemical precipitation or ion exchange processes it is often technically feasible to remove and concentrate in a solid form the contaminants, permitting the aqueous phase to be released to a river or lake. However, under many circumstances this approach provides insufficient decontamination or is excessively costly and results in large volumes of solid or semi-solid residuals that must be given further processing and stored. In the situation of a strontium 90 bearing waste the maximum concentration permitted in fresh water that may be used for drinking is so small that costly evaporation may be the only process giving adequate decontamination. For example, only a very small fraction of the daily strontium 90 production of a 100 megawatt reactor located on a river the size of the Columbia could be discharged to the river without endangering downstream water users.

Deep formations of the earth represent an essentially untapped "resource" for the disposal of waste products. At present the only major utilization of earth disposal of radioactive wastes is at the Hanford Atomic Productions Operation in the State of Washington. In this instance a combination of isolation and low rainfall make possible the discharge of intermediate level wastes in shallow formations lying within a few hundred feet of the surface of the earth.

In order to appreciate the advantages and limitations of earth disposal it is necessary to consider the hydrogeology of the earth's crust. Waters may be arbitrarily classified as meteoric or connate. Meteoric waters are circulating between the oceans and the continents in what is often termed the "hydrologic cycle". Such waters are used by man, either directly or as a source of food and must be maintained at a relatively high degree of purity from the standpoint of contamination with nuclear wastes. Connate waters, often termed "fossil waters", are derived from ancient seas and show a strong tendency to be retained at a given location over geologic time. In many areas of the United States vast deposits of almost pure sodium chloride are found, resulting from the complete evaporation of a prehistoric lake or ocean. Even more extensive sandstone formations underlie great areas of the North American continent and contain connate brines of salinities ranging up to several times that of sea water. The very existence of these brines is conclusive evidence of the isolation of the sandstones from the circulating meteoric waters lying closer to the earth's surface. In many locations the isolation is assured by overlying clay strata which form impervious barriers to the entrance of connate water into the meteoric system.

Injection Disposal into Deep Formations

A connate water bearing formation represents an extremely attractive storage site for low and intermediate level radioactive wastes. There are several reasons for this. First, they are geologically stable and isolated as demonstrated by their existence for millions of years. Second; the capacity of such formations is enormous as they are often hundreds of feet thick and are thousands of square miles in areal extent. The waste storage capacity of a connate formation derives from two sources; the porosity, which ranges from 10 to 20 percent, and the ion exchange capacity contributed by the clay fraction of the formation, this amounting to as much as 20 or 30 milliequivalents per 100 grams. A particularly important aspect of using such formations for nuclear waste disposal is that the technology of introducing liquids into deep strata has been developed to a high state by the petroleum industry. For years the practice of introducing waste brines and other waters into oil bearing formations has been an integral part of petroleum production. The purposes served by such operations include secondary recovery of oil from depleted fields and maintenance of pressures for more economic pumping. It is thus apparent that a great potential storage facility is represented by the deep sandstone formations of the earth.

Numerous factors must be considered before a radioactive waste can be injected into a deep formation. In order for an aqueous waste to be introduced into a porous medium it must be free of suspended material that would clog the interstices through which the liquid is to pass. It should also be free of substances that would form precipitates on coming into contact with the connate water. The presence of organic matter that would promote bacterial growths and cause clogging must also be avoided. The problems are identical to those faced by the petroleum service company operating a water flood and can be resolved by conventional processes employed in industrial water conditioning. These include chemical flocculation, sedimentation, filtration, and chlorination. The pre-injection treatment would result in a highly radioactive solid or semi-solid sludge that could be fed into the high level waste handling system or dried and stored separately, depending on the local conditions.

The major problem in the development of an injection system is the selection of a suitable formation and the "proving" of the formation by exploration. Ideally, the injection formation should have a high permeability to reduce the resistance to fluid flow and pumping costs. It should be of great areal extent, not over 50 or 100 feet deep, and as nearly homogeneous as possible. For example, the existence of fractures or regions of very high permeability would permit the waste to bypass large masses of media and thus reduce the useful capacity. As will be considered in a subsequent paragraph, a high exchange capacity is also desirable in order to increase the retention of such radioisotopes as strontium 90 and cesium 137. The question of useful formation capacity is related to certain fundamental aspects of the mechanics of flow through porous media and to the equilibria and kinetics of ion exchange between the radionuclides and the clay fraction of the medium.

A schematic illustration of a deep well injection system at a central chemical reprocessing plant is shown in Figure 1. The relief well (or wells) serves several important functions. By enabling the displaced connate water to leave the receiving formation the natural static condition of the formation is essentially maintained. The likelihood of a breakout through the confining layers is thus greatly minimized and containment integrity is assured. The direction taken by the injected waste is determined by the pressure gradient. Since the maximum gradient will be in the direction of the relief well, the maximum rate of movement is toward a well that can be conveniently monitored. The effluent brine, and perhaps even a low level waste containing nuclides of small hazard, leaving the relief well may be discharged into an adjacent river or returned to the earth at a shallower depth. An actual disposal operation would involve a pattern of injection and relief wells arranged to make maximum utility of the storage capacity of the underlying formations and to provide near perfect containment. When excessive radioactivity appears at a relief well it may be taken out of operation and subsequently operated as an injection well. It is unlikely that wells constructed for the sole purpose of monitoring will be necessary. It is believed that such a system of wells penetrating a suitable formation would provide more permanent containment than man-made tanks located near the surface of the earth. Perhaps the only restriction to the operation of such a system would be the activity level of the waste and the heat produced during radioactive decay. For this reason deep injection does not appear promising for high level wastes, since the resulting high temperatures would create localized high pressures and tend to impair containment integrity.

Hydraulic Dispersion in Flow Through Porous Media

When water is introduced into a permeable formation the direction and average rate of movement is determined by the vector quantity describing the maximum potential gradient. It is a relatively simply matter to compute the average velocity of waste travel and to estimate when, on the average, the injected fluid will have moved some specified distance. Unfortunately the problem is somewhat more complex. Different portions of the liquid may be expected to move at different velocities, such that some small fraction may actually have a velocity several times the average. In the case of underground radioactive waste travel the phenomenon of velocity variation, which may be termed "dispersion", may result in the early arrival of the waste at the relief well and thus greatly reduce the effective capacity of a formation.

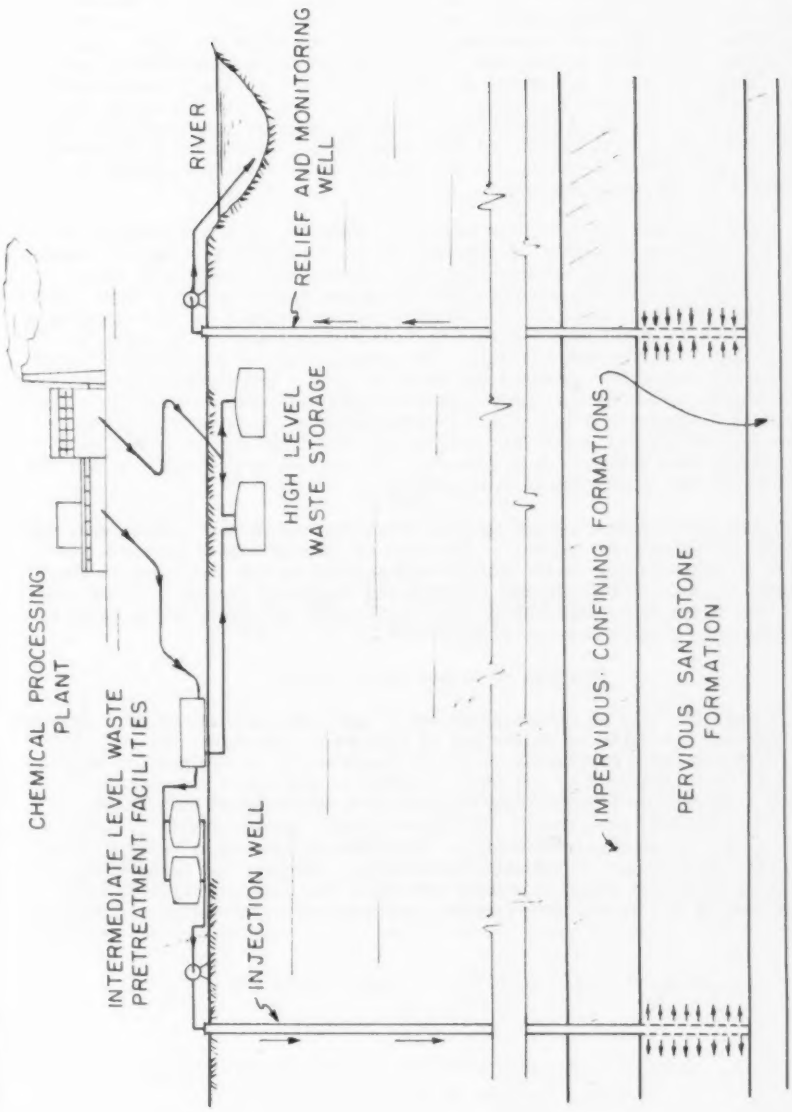


FIG. 1 A HYPOTHETICAL DEEP WELL DISPOSAL OPERATION

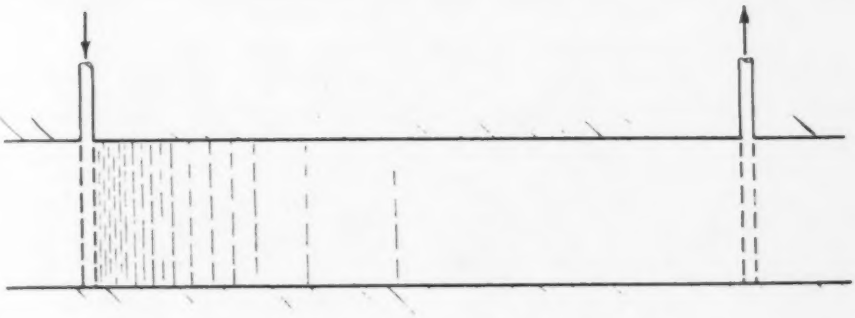
Dispersion, in the broadest sense, may originate from three causes. In a perfectly homogeneous and isotropic medium various stream lines will follow different paths and two "particles" of fluid, initially together, will become increasingly separated as they move along different paths at different average velocities. Dispersion of this type can be easily demonstrated in the laboratory with a column of carefully graded sand. A natural formation contains fractures and regions of low and high permeability which result in gross variations in velocity from point to point and a characteristic dispersion far greater than that observed in the laboratory column. This type of dispersion is often termed "fingering" and is one of the major limitations to the success of a secondary oil recovery operation. A third cause of gross dispersion is a difference in density between the injected waste and the displaced formation water. This difference may result in the creation of a wedge of waste water, over- or under-riding the formation water, and the early arrival of the waste at the relief well. These three causes of waste velocity variation are illustrated in Figure 2. Dispersion, as described herein, should not be confused with molecular diffusion which, due to its very small magnitude, makes practically no contribution to waste transport.

Laboratory and field studies have been conducted at the University of California with the objective of determining the fundamental nature of hydraulic dispersion and developing tracer techniques whereby this property of deep geologic formations may be measured with precision and certainty. These studies have shown that dispersion may be characterized by a single "medium dispersion constant" that is independent of velocity and distance and is, in fact, a unique property of the medium itself. In a field study of a natural confined formation the dispersion constant was found to have a magnitude of several feet. In laboratory studies of carefully packed columns the constant was only a few centimeters, illustrating the effect of heterogeneity on velocity variations and the desirability of selecting homogeneous formations for waste disposal. Unfortunately this property of a formation can only be determined with the aid of test wells and direct tracer measurements.

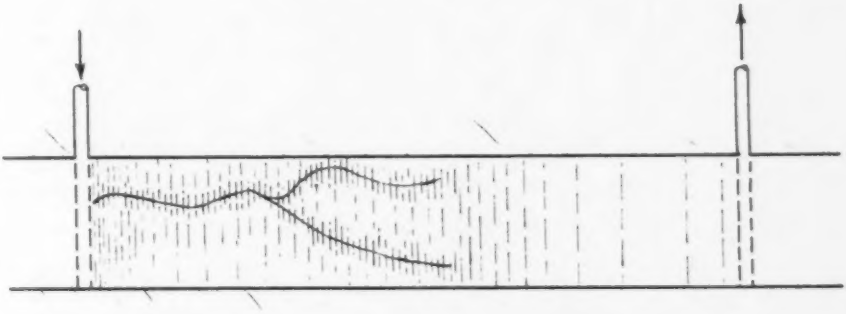
A laboratory model was employed to determine the factors influencing the magnitude of "density dispersion". The rate of density caused movement was found to be proportional to the formation permeability and depth and to the difference in density between the injected and displaced fluids. It was concluded that dispersion caused by density differences is likely to be small in comparison with other causes of dispersion.

Studies of Ground Water Tracers

Perhaps the only satisfactory method of geologic exploration of a proposed waste disposal formation is by the use of test wells and water tracers. The presence of extensive fracturing is easily demonstrated by the tracer test, but cannot be ascertained by any other geophysical exploration technique. Numerous chemical and radioisotopic tracers were investigated and tested in field and laboratory experiments. In surface water tracing a wide variety of substances are reasonably satisfactory, depending on the requirements of the particular application. In ground water tracing, however, the adsorptive capacity of the earth material greatly restricts the choice of tracer. For example, nearly all of the radioisotopes are unsatisfactory unless accompanied



DISPERSION IN A HOMOGENEOUS MEDIUM



DISPERSION IN A FRACTURED OR
NON-HOMOGENEOUS FORMATION

DISPERSION RESULTING FROM DENSITY EFFECTS
$\rho_1 < \rho_2$

FIG. 2 HYDRAULIC DISPERSION IN FLOW
THROUGH POROUS MEDIA

by large concentrations of their stable isotopes, a procedure that is generally costly and impractical.

The tracer selected for full scale field testing was tritium in the chemical form of tritiated water. Tritium, though having a radioactive half-life of 12.5 years, is one of the least hazardous of the radionuclides. Its biological half-life is only 12 days and the energy of its beta radiation is extremely low, so low, in fact, that it represents one of the major obstacles to its detection. The problems of tritium measurement have been largely overcome with the development of the liquid scintillation counter and techniques for introducing a large sample of water into the chamber of the counter. Liquid scintillation counting of tritium is relatively simple, requires a minimum of technician experience, and is making possible the application of tritium to the solution of a wide variety of engineering problems. It is believed that tritium is perhaps one of the very few completely reliable ground water tracers for problems involving long periods of time and great distances of travel that, further, meets the engineering requirement of ease and economy of measurement.

Another tracer of some interest is helium. Comparisons of helium and tritium passage through soil columns show both tracers to be equally satisfactory from the standpoint of adsorptive loss. Methods of extracting helium gas from water and measuring it at extremely low concentrations, in the order of a few tenths of a part per billion, have been developed and will make this tracer available for general use. The major limitation of helium is its low solubility in water and a resulting tendency to "outgas" and form bubbles in the media. This phenomenon can be avoided by maintaining a sufficient partial pressure of helium, but will restrict its use to pressure aquifers and deep connate water bearing formations. Another consideration in the use of helium is the natural helium content of water originating in mineral deposits of uranium and thorium.

Ion Exchange in Natural Media

One of the most attractive aspects of injection disposal of radioactive wastes is the adsorption of the nuclides by the porous medium. The ion exchange capacity of sandstone formations, though small, will serve to greatly enhance the storage value of such formations for low and intermediate level wastes. An aqueous solution of radioisotopes moving through a formation will bring about a chromatographic separation of the isotopes such that each species will advance at a particular velocity, a velocity often far less than that of the waste water.

Figure 3 will serve to illustrate the occurrence of selective sorption during the injection of a fission products waste. The two most physiologically important nuclides in such a waste would generally be strontium 90 and cesium 137 and these have been used in the illustration. The sorptive characteristics of these isotopes have been measures for several typical California oil sands and such stable cations as calcium and sodium. Having measured the equilibrium constants of cesium and strontium, and knowing the waste composition, it becomes possible to predict the rate of advance of these nuclides and to compute the effective storage capacity of a formation receiving such a waste. Making reasonable assumptions as to waste composition, it becomes possible to predict

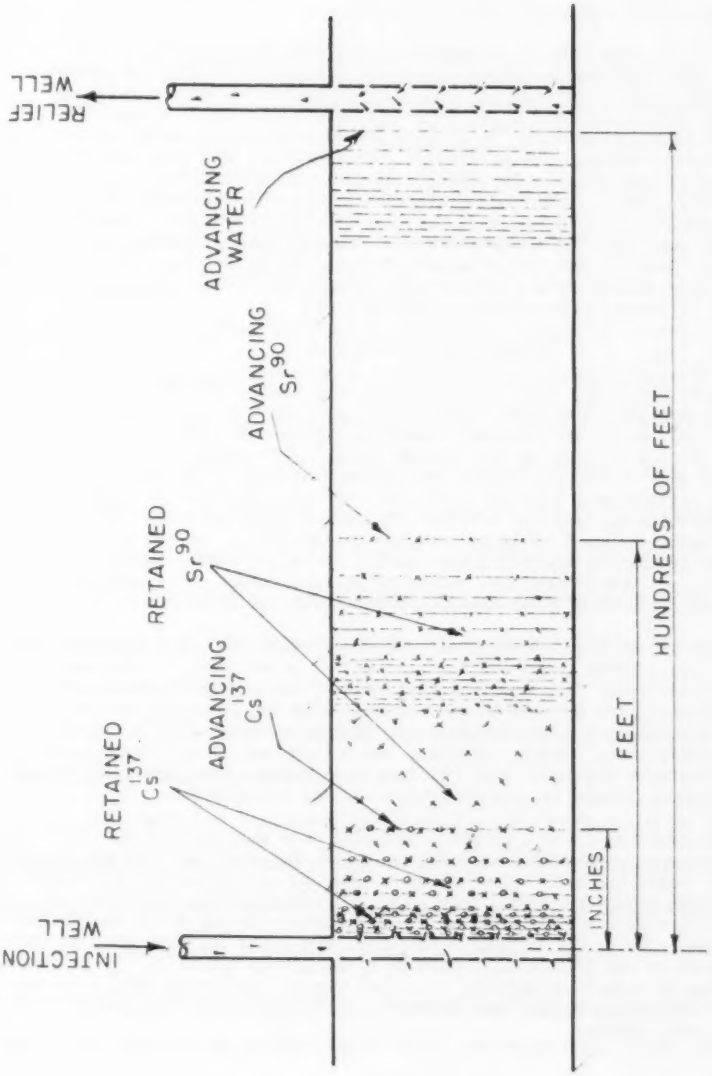


FIG. 3 SEPARATION OF ISOTOPES BY SELECTIVE ADSORPTION IN A GEOLOGIC FORMATION. STRONTIUM and CESIUM

the rate of advance of these nuclides and to compute the effective storage capacity of a formation receiving such a waste. Making reasonable assumptions as to waste composition and formation exchange capacity, it can be shown that the relative velocities of water, strontium 90, and cesium 137 would be in the order of one foot per day, one foot per month, and one foot per year, respectively. One square mile of a formation 50 feet thick having a porosity of ten percent could contain 140 million cubic feet of liquid. However, the same formation could receive four billion cubic feet of a waste containing strontium 90 prior to the arrival of the radionuclide at a relief well.

A small scale field study of injection disposal was conducted at the Sanitary Engineering Research Laboratory of the University during the summer of 1957. A simulated waste containing trace concentrations of strontium 89 and cesium 134 was introduced into a confined aquifer at a depth of 90 feet. The injection rate was approximately 35 gallons per minute and the waste injection continued for seven weeks. Water, free of radioactivity, was then introduced for several additional weeks. By taking samples at 23 observation wells it was possible to follow the movement of the strontium up to 63 feet from the injection well. No cesium was observed at even the closest observation well located at a distance of 13 feet from the injection well. Correlative laboratory tests of formation cores demonstrated the movement of strontium to be predictable. Cesium was retained to a considerably greater degree than predicted by the kinetic theory of ion exchange developed for column systems.

Summary and Conclusions

The injection of radioactive wastes into deep geologic formations is considered a feasible and economic approach to handling low and intermediate level wastes. As in the case of many engineering problems, deep injection does not represent a panacea for all nuclear wastes, but rather is one possible solution to be arrived at only after considering the factors peculiar to a given situation. In selecting a site for a central chemical reprocessing plant the matter of a suitable geology for disposal of low and intermediate level wastes into deep formations should be given careful consideration. In the past it has been customary to utilize the dilution capacity of large bodies of water for waste disposal. In the future development of nuclear energy it is unlikely that such simple and often questionable practices will be tolerated.

The basic research and development associated with deep well injection has been underway for several years and has reached the point where a full scale field test is indicated. The chemical treatment of low and intermediate level wastes will be necessary to make them compatable with the receiving formation, but should represent no particular problem. If the wastes at a site vary widely in chemical composition, holdup, blending, and testing may be necessary prior to chemical treatment and injection. It is almost certain that the preinjection treatment operation should include filtration and pH adjustment.

Detailed exploration of a proposed disposal site will require the application of the most advanced geophysical methods, including the drilling of test wells and the use of water tracers. Information determined by passing typical waste solutions through formation cores, coupled with field measurements of the dispersion properties of the formation, will make possible a completely engineered disposal system. The useful formation capacity, and hence the unit cost of the injection phases of the operation, should be a calculable quantity. It is believed that the system of injection disposal described herein, employing both injection and relief or monitoring wells, will provide economic and safe containment of intermediate level wastes.

UNDERGROUND MOVEMENT OF RADIOACTIVE WASTES

By

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The transport of radionuclides by the subsurface waters of the earth has an important bearing on the environmental hazard created by the waste fission products of the nuclear energy industry. The alternative systems for handling the wastes of this industry are limited to confinement and dispersal. Unfortunately, the extremely small concentrations of the more hazardous radioisotopes permitted in drinking water essentially preclude disposal by dilution of any but the lowest level wastes and of relatively small quantities of such isotopes as strontium 90. Nuclear industries located in arid regions of the West often have no surface dilution water available to them and may be required by apprehensive regulatory agencies to produce an effluent completely devoid of radiocontaminants. Under these circumstances, conventional methods of dispersal are out of the question, and complete confinement, perhaps preceded by a concentration process, represents very nearly the only solution.

In situations involving high-level wastes containing up to several hundred curies per gallon, prolonged storage is an unavoidable aspect of chemical processing and must precede any final containment. Under these circumstances there exists the possibility of accidental contamination of potentially useful ground-water. An investigation of this potential hazard must obviously be an integral part of a site-selection study, particularly as a competitive nuclear industry faces the necessity of locating its plants near population centers.

Where small volumes of low or intermediate level wastes are produced, concentration of the radioactive fraction before storage is indicated. However, larger volumes of such wastes pose a costly problem in volume

reduction, particularly if stringent effluent requirements are to be met. Under these circumstances, underground formations of the earth represent an attractive storage or retention resource worthy of consideration. Although this method of disposal is not without precedent, the disadvantage of a system entailing the free discharge of a hazardous material into the ground is obvious. The most serious objection evolves from the uncertainty as to where and when it will appear in some community's water supply. In spite of this admitted possibility, the great capacity of the material of the earth to adsorb trace concentrations of radioelements strongly indicates the desirability of investigating methods of ground disposal.

In designing a free-discharge disposal system, the probability of contaminating potentially useful ground or surface water must be reduced to an absolute minimum. Systems most nearly meeting this criterion appear to fall into two categories. Surface or subsurface spreading systems are indicated where the ground-water table is overlain with several hundred feet of unconsolidated media and the local precipitation is low. The ion-exchange capacity of the earth column serves to retain the cationic waste components and, if additions of liquid cease when the most rapidly moving hazardous component reaches the zone of saturation, a highly permanent retention is achieved. Important considerations in the design of such a system include the infiltration capacity of surface strata, the formation permeability and its variation with direction and distance, and the exchange capacity for the more hazardous radio-isotopes.

The second type of disposal system consists of the injection of the wastes into deep formations, well below the zone of circulating or meteoric waters. Deep sedimentary formations generally contain connate, or fossil, water that has migrated relatively little over geologic time. The interstitial

space of such connate-water bearing sands may well constitute a far more permanent natural container than man has yet devised. Furthermore, the exchange capacity of many connate formations will contribute greatly to the storage capacity and permanence of this natural container.

The design of disposal systems of this type requires a compatability of the waste and the media of the disposal site; there must be an absence of particulates and precipitate-forming chemicals. With this criterion met, it is then necessary to predict the direction and velocity taken by the various radiocomponents. The direction and average velocity are determined by the hydraulic gradient and porosity, and, when the medium is unsaturated, by the existence of capillary forces. The occurrence of longitudinal mixing or hydraulic dispersion results in some portions of the waste traveling at velocities considerably greater than the average. In an ideally homogeneous and isotropic medium, this phenomenon would be minimal, but not entirely eliminated. In a natural formation, dispersion, perhaps together with fingering, can play a determining role in limiting the utility of a site. The movement of trace radioelements is dependent not only on the velocity of the transporting liquid, but also on the exchange capacity of the medium for the individual nuclides. Since ion-exchange is not instantaneous, primarily due to the rate-limiting effects of diffusion, wide variations in the velocity of a single trace component are likely to occur. A complex interplay of physical and chemical parameters is thus seen to determine the manner in which a radioactive contaminant will move through the earth's crust.

The purpose of this paper is to outline quantitatively the basic relationships determining: 1) the extent of hydraulic dispersion, 2) the exchange capacities of several natural media for radiostrontium in the presence of such interfering cations as hydrogen, sodium, and calcium, and

3) the influence of rate-controlling steps in ion-exchange contributing to variations in the velocity of strontium movement and limiting the useful storage capacity of an underground formation.

Hydraulic Dispersion in Porous Media

When one aqueous solution displaces another in a saturated porous medium, the boundary, or "front," between the two solutions becomes progressively more diffuse as the distance traveled increases. In the absence of ion-exchange, the diffuseness is due almost entirely to microvariations in velocity within individual pores and from one pore to another. When cations in the displacing liquid enter into exchange reactions with the medium, these reactions may be expected to make an additional contribution to the diffuseness or depth of the front bounding the influent cations. This latter effect can, under certain circumstances, cause a far greater degree of dispersion than brought about by liquid velocity variations. Molecular diffusion is insignificant in comparison with dispersion resulting from liquid displacements. A quantitative description of dispersion is provided by breakthrough curves obtained by plotting the effluent concentration of a component as a function of time or effluent volume. The slope of the S-shaped breakthrough curve may serve as an index of dispersion.

Owing to the complexity of the flow channels in natural granular material, hydraulic dispersion in laminar flow is best analyzed by a semi-empirical approach, assuming a random type of diffusion described by Fick's Law. Rifai[1] has expressed this relationship by the differential equation,

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - S \frac{\partial c}{\partial x} ,$$

in which c is the component concentration, x the distance traveled, S the

linear velocity and D the dispersion constant. In order to apply this equation to the analysis of saturated column systems, its solution may be used expressed in terms of the throughput volume V, the pore volume vf, and the column length L:

$$c/c_o = 1/2 \left[1 - \text{erf} \frac{1 - (V/vf)}{2\sqrt{(\frac{D}{LS})(V/vf)}} \right] \qquad (1)$$

It is seen that equation (1) is a single-parameter family of curves relating the normalized effluent concentration, c/c_o, to the normalized throughput volume V/vf. The parameter is the dimensionless group (D/LS).

Studies of Ottowa and Monterey sands by Rifai[1] and Krone and Orlob's[2] investigations of Oakley sand, have shown approximately linear relationships between the dispersion constant D and the linear velocity S, i.e., $D = D_m S$. This relationship stems from the fact that the shape of the breakthrough curve is nearly independent of the flow rate over a range of from 5×10^{-4} cm/sec to about one cm/sec in media having an effective size of approximately 0.45 mm and a uniformity coefficient of 1.3. Equation (1) may thus be rewritten as

$$c/c_o = 1/2 \left[1 - \text{erf} \frac{1-(V/vf)}{2\sqrt{(D_m/L)(V/vf)}} \right]. \qquad (2)$$

A plot of equation (2) is shown in Figure 1, D_m being the medium dispersion constant and presumably dependent on such factors as effective size, uniformity coefficient, and particle shape. The validity of equation (2) has been demonstrated for column systems of relatively uniform grain size in which dispersion occurs only in the longitudinal direction. Field-scale studies of chloride dispersion in radial flow from an injection well have provided breakthrough data that follow closely the curves shown in Figure 1. It is thus apparent that at least for the single dimension case, the measurement of a

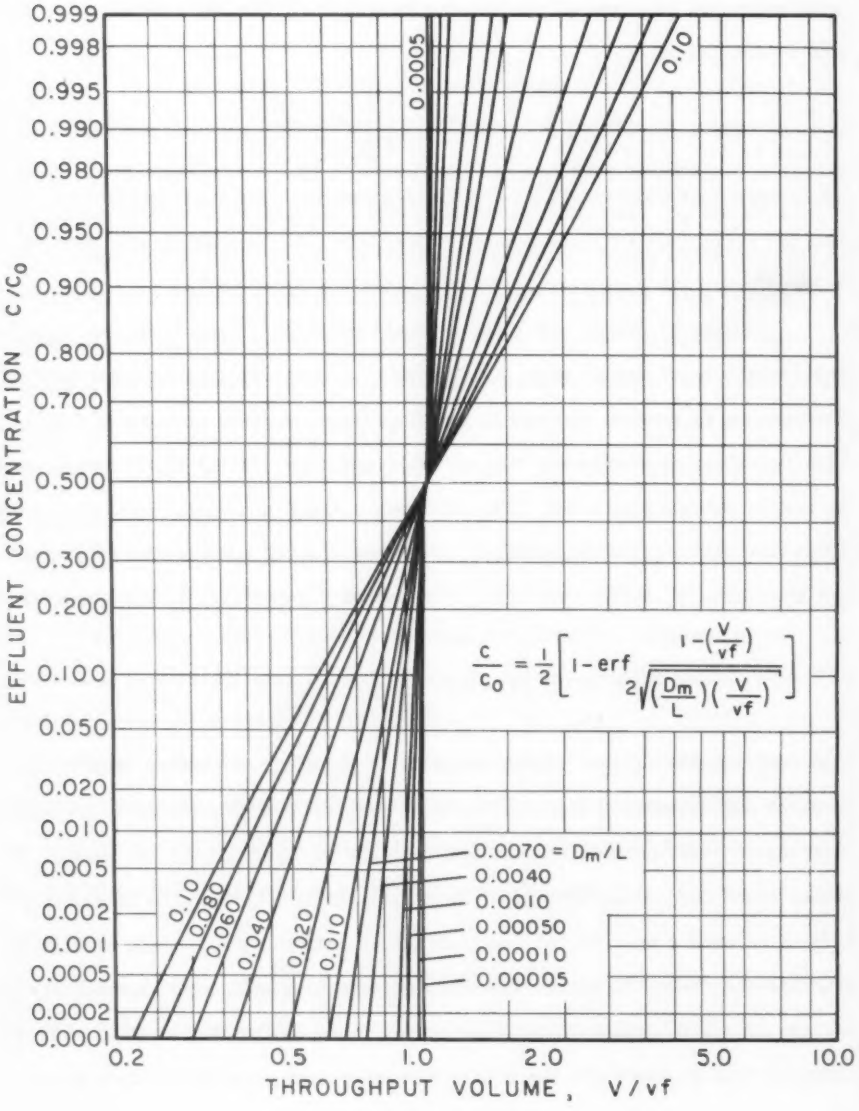

FIG. 1 GENERALIZED HYDRAULIC DISPERSION CURVES

single breakthrough curve on a column of known length permits the determination of the medium dispersion constant D_m. The breakthrough curves for longer columns of the same medium can then be selected from Figure 1. Such curves can be employed in estimating the maximum rate of travel of an inert component of an injected waste. Heterogeneities in the stratigraphy of a disposal site will of course place serious limitations on the reliability of this method. However, many of these uncertainties may be eliminated by the exploration of a formation with a harmless tracer prior to beginning waste injection.

Ion-Exchange Phenomena

The theories of ion-exchange in flow processes, as developed by Thomas[3][4], and adapted to chemical engineering use by Hiester and Vermeulen[5], are based on differential equations describing material balances and kinetic relationships. Ion-exchange capacity, equilibrium constants and rate coefficients are generally assumed to be true constants representing the characteristics of a single homogeneous medium. The effects of hydraulic dispersion are not considered. The reasonably good agreement between the experimental results of numerous workers and these theories can probably be attributed to the fact that high-capacity resins were employed so that hydraulic dispersion became a negligible quantity. Furthermore, some degree of empiricism is inherent in mathematical expressions of such complex phenomena as ion-exchange in columns.

Hiester and Vermeulen[5] have prepared several families of generalized breakthrough curves with which experimental data may be compared and from which certain parameters characterizing the reaction kinetics may be derived. One of these families, corresponding to the breakthrough of a trace component is shown in Figure 2. For this condition, the equilibrium parameter r is

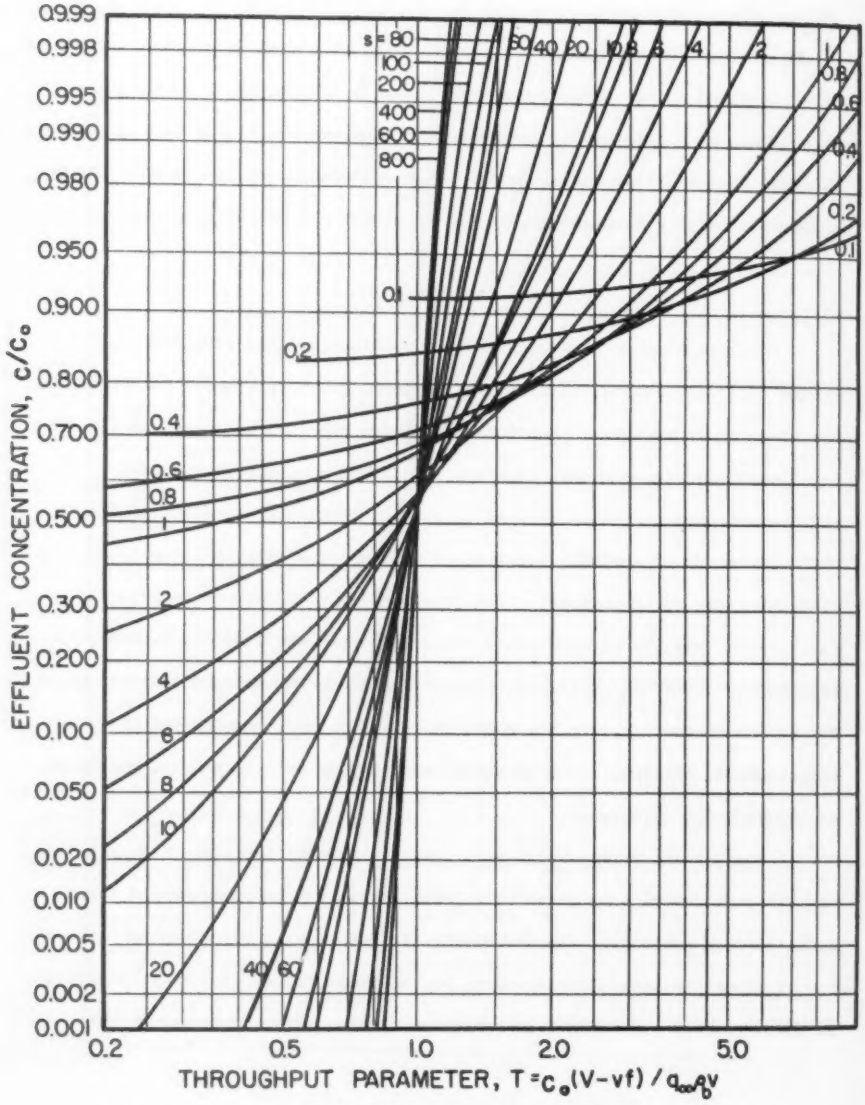

FIG. 2 - GENERALIZED BREAKTHROUGH CURVES, r = 1

equal to unity. This case is of special significance in the problem of radioisotope travel. When the waste component is present in an appreciable concentration, r, computed from equation (3) may no longer be unity and Figure 2 would not be applicable.

$$r_A = \frac{1}{1 + \left[K''_A - 1\right](c_A)_o/c_o} , \qquad (3)$$

where $(c_A)_o$ is the concentration of component A, and c_o is the total concentration of exchangeable cations, in the influent. K''_A is a modification of the mass-action constant, defined by the expression

$$K''_A = \left[\left(\frac{c_B^{\,a}\, q_A^{\,b}}{c_A^{\,b}\, q_B^{\,a}}\right)\left(\frac{q_A + q_B}{c_A + c_B}\right)^{a-b}\right]^{2/a+b} \qquad (4)$$

corresponding to the replacement of ion B by ion A as given by equation (5).

$$bA^{+a} + B_a \cdot \text{clay} \leftrightharpoons aB^{+b} + A_b \cdot \text{clay}. \qquad (5)$$

The term $(c_B^{\,a} \cdot q_A^{\,b}) \div (c_A^{\,b} \cdot q_B^{\,a})$ in equation (4) is the mass-action constant in which c_A and c_B are the solute concentrations in meq/ml and q_A and q_B are the equilibrium concentrations of A and B in the solid phase expressed in meq/gram. The valences of A and B are a and b, respectively. For symmetrical exchange, i.e., a = b, K''_A equals the mass-action constant.

The abscissa of Figure 2 is a dimensionless throughput parameter,

$$T_A = (c_A)_o(V - vf)/(q_A)_{\infty}\rho_b v, \qquad (6)$$

analogous to the normalized throughput volume, V/vf, used in the analysis of hydraulic dispersion (Figure 1). The ultimate concentration that component

A can reach in the solid phase is $(q_A)_\infty$, corresponding to a solute concentration of $(c_A)_o$ in the influent. v and ρ_b correspond to the gross volume and the bulk density of the medium. Each curve is characterized by s, the "column capacity parameter" as defined by

$$s = k(vf/R) = k(L/S) , \qquad (7)$$

where k is the general rate constant and R the volumetric flow rate. The column capacity parameter is analogous to D_m/L as previously discussed. It may be well to discuss qualitatively the effect of certain factors on the configuration of the breakthrough curves. These factors may be considered in two categories; (1) those influencing the shape of the normalized breakthrough curves and, (2) those entering into the definition of T by equation (6), and thus transforming the normalized plots into a direct relationship of V and c/c_o.

The factors governing the shape of the breakthrough curve are the equilibrium parameter r, the column capacity factor s, and whether external or internal diffusion is the rate-determining mechanism. The advancing front is sharpest at low values of r and high values of s. In the case of trace-components, r is very nearly equal to one. For the binary exchange of gross components, favorable equilibria, corresponding to values of the mass-action constant above unity, contribute to the sharpening of the breakthrough front. Large general rate coefficients and small flow rates also serve to steepen the breakthrough curve (cf. equation (7)). For a more detailed discussion of the general rate coefficient, the reader is referred to the literature[5][6]. By referring to equation (6), it is noted than when T = 1, a volume of liquid (V) has entered the column, sufficient to fill the pore volume vf and containing an amount of component A equal to the ultimate exchange capacity,

$(q_A)_\infty \rho_b v$ for that component at concentration $(c_A)_o$. The volume corresponding to T = 1 may be termed the "average breakthrough volume" and can be computed from the expression $\bar{V}_A = vf + (q_A)_\infty \rho_b v / (c_A)_o$. Since $vf/\bar{V}_A$ equals the ratio of the average linear velocity F_A of component A, to the average fluid velocity S,

$$F_A/S = 1/\left[1 + (q_A)_\infty \rho_b/(c_A)_o f\right] . \qquad (8)$$

For the simple case of a single cationic species displacing another, q_∞ is the total exchange capacity of the medium and the ratio F/S is dependent almost entirely on the influent concentration, ρ_b/f being essentially constant for natural media. In the more complex case of several exchanging cations, the capacity of the medium for a particular component $(q_A)_\infty$ will depend on $(c_A)_o$ and the equilibria existing between A, the gross components of the system, and the medium. As the column length is increased, the slope of the breakthrough curve becomes relatively less significant and the average velocity assumes greater importance.

Studies of Ion-Exchange Equilibria

The purpose of the laboratory studies was to measure the parameters determining the average displacement and dispersion of trace strontium fronts in their passage through natural porous media. The three most important parameters have been shown to be: 1) the exchange capacity, 2) the equilibrium constant, and 3) the general rate coefficient. The materials studied included a California agricultural soil, several typical California oil sands, and an American Petroleum Institute standard halloysite clay. The first two materials were chosen as representative of deep connate-water bearing formations and surface soils. The solutions employed contained one ppm of

stable strontium and were otherwise relatively simple in composition. No attempt was made to simulate any particular radioactive waste.

Determination of Exchange Capacities: The studies were conducted with both column and batch systems, depending on the particular parameter under investigation. The columns were 19 mm I.D. with a length of 3.5 in., unless otherwise noted. They were generally presaturated with a known solution in order to simplify the interpretation of the breakthrough data. For example, when the exchange of calcium and strontium with sodium was examined, the columns were presaturated with a simulated connate brine (0.09N NaCl and 0.06N $NaHCO_3$). The batch experiments were used to determine certain of the exchange capacity and equilibria data. The media were presaturated with successive portions of a solution of traced cations until no further uptake was indicated. The tracers were then removed by successive elutions with a solution chemically identical to the saturating solution but free of radioactive tracers. The exchange capacities and equilibrium constants were then computed from radioassay data and the known cation concentrations of the saturating solution. A summary of the exchange capacity determinations is shown in Table 1.

The measured exchange-capacity is known to depend often on the laboratory procedure employed. Therefore, a method should be chosen duplicating as nearly as possible the conditions expected in the field where the results are to be applied. To ascertain whether equilibrium was reached in columns, it was considered desirable to determine the exchange capacity by both batch and column methods, as well as by the standard ammonium acetate procedure. Fair agreement was observed among the various methods, except for the Yolo soil and halloysite.

TABLE 1
EXCHANGE CAPACITIES

Material	Exchange Capacities, meq per 100 g.		
	Column $Ca + Ca^{45}$	Batch $Ca + Ca^{45}$	Ammonium Acetate
Sands:			
Coalinga	0.3	-	0.2
Dominguez	5.7	5.6	5.6
Lost Hills*	13.0	-	14.1
Richfield	2.4	-	2.4
Rosecrans	4.7	4.3	4.3
Halloysite Clay*	14.9	8.7	10.8
Yolo Soil*	25.1	25.6	15.2

Saturating solution was 0.1N Ca^{++} traced with Ca^{45} and 2.28×10^{-5}N Sr^{++} (1 ppm.). The effluent pH ranged from 7.3 to 7.7.
* Mixed with an equal weight of acid-washed asbestos (Gooch Grade, Merck) to improve permeability.

The measured exchange-capacity is known to depend often on the laboratory procedure employed. Therefore, a method should be chosen duplicating as nearly as possible the conditions expected in the field where the results are to be applied. To ascertain whether equilibrium was reached in columns, it was considered desirable to determine the exchange capacity by both batch and column methods, as well as by the standard ammonium acetate procedure. Fair agreement was observed among the various methods, except for the Yolo soil and halloysite.

Effect of pH on Exchange Capacity: Owing to the wide range of hydrogen-ion concentrations found in the wastes from the reprocessing of nuclear fuel elements, it is important to evaluate the effect of pH on ion-exchange equilibria. The study of pH presented in this section was prompted by the necessity of determining if a calcium-strontium system was essentially a two-component system or whether the omnipresent hydrogen ion seriously influenced

the measured exchange capacities and equilibrium constants. It is appreciated that the limited data reported are adequate only to illustrate the general effect of the competing hydrogen ion on the quantities of sorbed calcium and strontium ions.

The halloysite clay and the Dominguez sand were selected for study. The procedure was identical to the batch technique described in the previous section. Samples of the two media were brought into equilibrium with a traced 0.01N Ca and 2.28×10^{-5}N Sr solution at pH values ranging from 2.3 to 7.2. The sorbed cations were then removed and measured by radioassay. The equilibrium concentrations of sorbed strontium at various values of pH are shown in Figure 3. The corresponding change in the calcium exchange capacity ranged from 1 to 9 meq per 100 g. for halloysite and from 3 to 6 meq per 100 g. for the Dominguez sand. The effect on halloysite may be ascribed to the competitive action of the hydrogen ion. In the case of Dominguez sand, the dissolution of calcium carbonate from the medium caused an apparent reduction in the calcium capacity.

Measurement of Equilibrium Constants: The equilibrium constant determines not only the average rate of movement of a cation through porous media, but may also influence the degree of dispersion of the concentration front. Unfavorable equilibria result in greater average rates of waste travel and greater dispersion of the advancing front. The laboratory studies reported in this section include the measurement of equilibrium constants for strontium replacing calcium (K''_{Sr-Ca}) and calcium replacing sodium (K''_{Ca-Na}). In addition, the influence of sodium and hydrogen ion on the strontium-calcium equilibrium has been considered.

For the measurement of K''_{Sr-Ca} (cf. equation (4)), parallel column and batch systems were saturated with a solution containing 0.01N Ca and $2.28 \times$

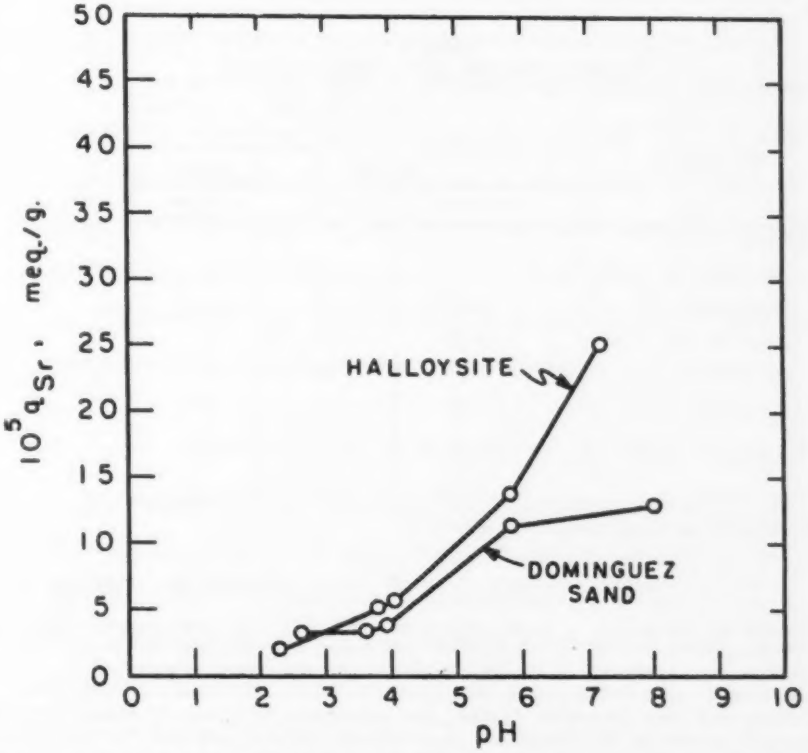

FIG. 3- EFFECT OF pH ON PARTIAL EXCHANGE CAPACITY FOR STRONTIUM

10^{-5} N Sr traced with Ca^{45} and Sr^{89}. The tracers were then eluted and the quantities of sorbed calcium and strontium determined by radioassay. Data for calcium (q_{Ca}) are those reported as exchange capacities in Table 1. Values of K''_{Sr-Ca} are presented in Table 2. It was also possible to obtain q_{Ca} and q_{Sr} during the saturation step of the column experiments.

TABLE 2
STRONTIUM-CALCIUM EQUILIBRIUM CONSTANTS

Material	$K'' = \frac{c_{Ca}\, q_{Sr}}{c_{Sr}\, q_{Ca}}$, a = b = 2		
	Column		Batch
	Saturation	Elution	Elution
Sands:			
Coalinga	-	1.61	-
Dominguez	1.29	0.98	1.15
Lost Hills*	1.53	1.40	-
Richfield	1.48	1.28	-
Rosecrans	1.28	1.26	1.23
Halloysite Clay*	1.68	1.34	1.31
Yolo Soil*	1.38	1.17	1.21

* Mixed with an equal weight of asbestos.

The comparative constancy of the K" values obtained for materials as different as the sands, a relatively pure clay, and the agricultural soil, is of particular interest. Although the exchange capacities of natural materials may vary over wide limits, the relative affinities of these materials for strontium and calcium appear to remain nearly constant. Laboratory studies currently in progress indicate that equilibrium conditions are very slowly reached in certain media and suggest a possible source of error in the constants shown in Table 2. However, the batch data agree fairly well with the column studies, serving to support the accuracy of the data reported at this time. If the 0.98 values for Dominguez sand is excluded, it may be

concluded that strontium is more favorably sorbed than calcium and that the strontium breakthrough curve for a calcium or sodium-saturated medium should be comparatively steep. Both of these observations imply that natural media exchange preferentially with strontium and that a relatively efficient utilization of underground formations is possible.

The effect of pH on the strontium-calcium equilibrium constant is shown in Figure 4. These values were computed by equation (4) from data obtained in the experiment concerned with the influence of pH on exchange capacity. It is apparent that a reduction in pH effected a greater relative reduction in strontium than in calcium uptake. In a subsequent experiment, the presence of 0.09N sodium was observed to bring about an increase of the $K''_{Sr\text{-}Ca}$ for Rosecrans sand from 1.3 to 1.8, an effect opposite from that observed with increasing hydrogen-ion concentration.

Ion-Exchange Kinetics in Natural Media

The influence of the ion-exchange equilibrium constant and the column-capacity parameter was described in a previous section dealing with the kinetic theory. To illustrate the applicability of the theory to natural exchange media and the kinetic characteristics of various media, several column experiments were conducted on the material previously discussed. The influence of the equilibrium constant on the breakthrough curve is shown by Figure 5. In the case of self-exchange of calcium ($r = K'' = 1$), the equilibrium was favorable and the breakthrough relatively sharp. In the case of 0.1N sodium displacing calcium, the equilibrium was unfavorable ($K''_{Na\text{-}Ca} = 0.19$) and a flat breakthrough resulted.

Influence of the Column-Capacity Parameter on Dispersion: The column-capacity parameter (s, cf. equation (7)) influences the degree of dispersion

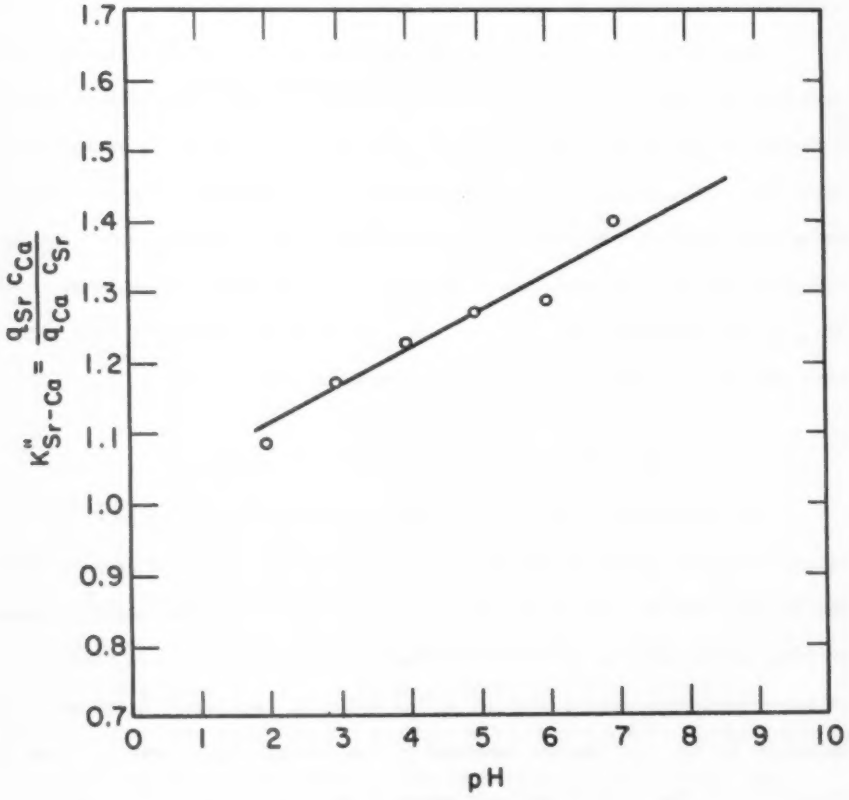

FIG. 4 - EFFECT OF pH ON K''_{Sr-Ca} - HALLOYSITE

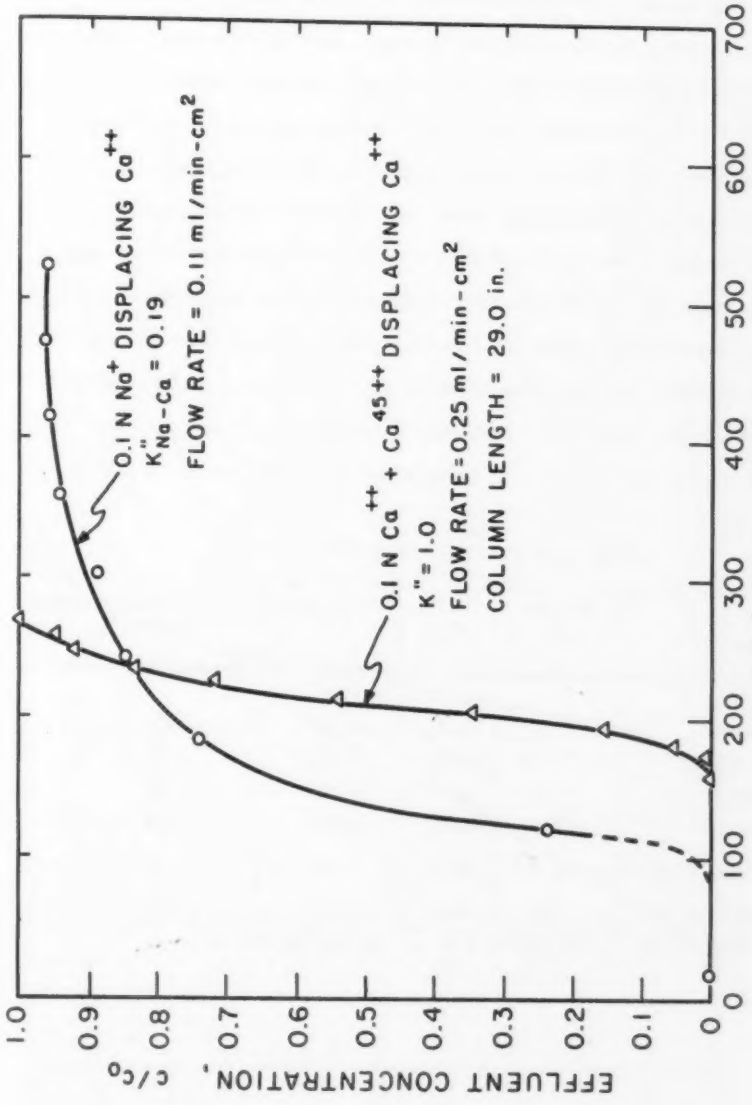

FIG. 5 - EFFECT OF EQUILIBRIA ON DISPERSION-ROSECRANS SAND

as shown in Figure 2; the larger s the less the relative diffuseness of the advancing front. The general rate coefficient k is dependent on the diffusivity of the exchange cations and the resistance of the medium. By passing a traced solution of 0.01N Ca and 2.28 x 10^{-5}N Sr through columns of the various media saturated with 0.09N Na, it was possible to obtain breakthrough curves for strontium and calcium. Although the equilibrium constants for calcium-sodium were not determined for each system, it may be inferred from the Rosecrans sand study that the equilibrium was favorable in each instance. In order to evaluate the contribution of hydraulic dispersion, chloride breakthrough curves were measured for each column. From these curves it was concluded that hydraulic effects were making only an insignificant contribution to front dispersion of the exchanging cations.

The breakthrough curves for strontium are shown in Figure 6. The throughput volume V has been normalized to aid in comparing media of widely different exchange capacities. Pertinent data describing the conditions of each run are given in Table 3. It is apparent that differences in the

TABLE 3
COLUMN DATA-STRONTIUM BREAKTHROUGH
(Figure 6)

Material	Weight $\rho_b V$ g.	Voids vf ml.	Flow Rate R/a ml/min.-cm^2	Average Breakthrough Volume, $\bar{V}_{Sr}$ ml.
Sands:				
Dominguez	37.3	13.7	0.023	294
Lost Hills	7.25	21.5	0.032	199
Richfield	42.6	14.4	0.050	158
Rosecrans*	27.5	12.0	0.040	180
Halloysite Clay	14.8	19.1	0.014	395
Yolo Soil	15.4	18.0	0.003	565

* Column length 3.0 in.,all others 3.5 in. pH ranged from 8 to 9.

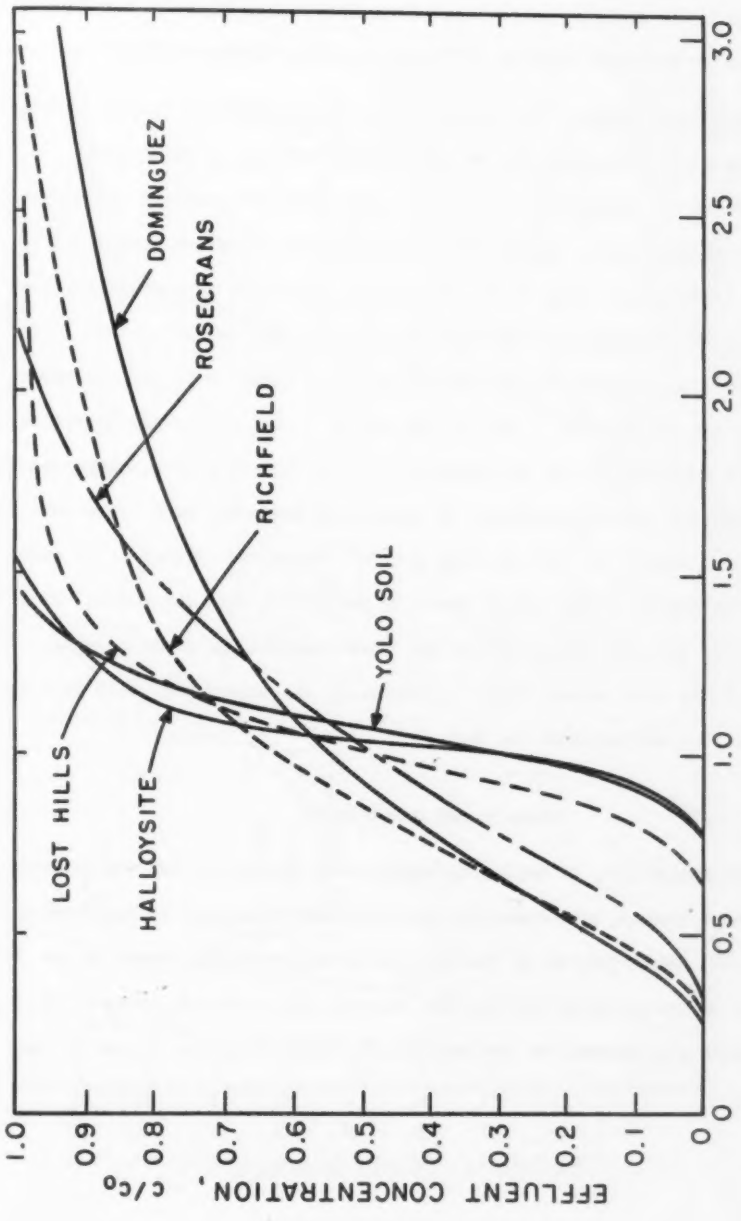

FIG. 6 - STRONTIUM BREAKTHROUGH - NORMALIZED PLOTS

dispersion effect caused by various media must be attributed to rate phenomena and are dependent on particle size and mass-transfer coefficients. The configuration of the corresponding calcium breakthrough curves for each medium was quite similar, indicating a relative independence of the internal resistance of the ionic species diffusing into the exchange sites.

Effect of Column Length: The influence of column length or "travel distance" on the degree of dispersion of concentration fronts is of particular importance in the design of underground waste disposal systems. Since the general rate coefficient should remain independent of column length, it is possible to determine this factor on a short column and subsequently employ it to predict the breakthrough characteristics of a much larger system. The direct field application of this relationship is possible by the employment of a small-scale field study to aid in the design of the full-scale operation.

The independence of the general rate coefficient k from column length was studied for the self-exchange of calcium in Rosecrans sand. The results are shown in Figure 7. By comparing the Ca^{45} breakthrough curves for each column with Figure 2, the column capacity parameters were estimated. From equation (7) the rate coefficients were then computed and found to equal 0.45 min^{-1} for each column, thus corroborating the theory that data from short columns may be extrapolated to long.

Summary and Conclusions

The feasibility of employing underground formations for the retention or permanent storage of radioactive wastes is dependent on: 1) the chemical and physical compatibility of the waste with the receiving formation and 2) the degree of certainty of predicting the velocity and direction taken by the more hazardous components of the waste. The first criterion is met if the

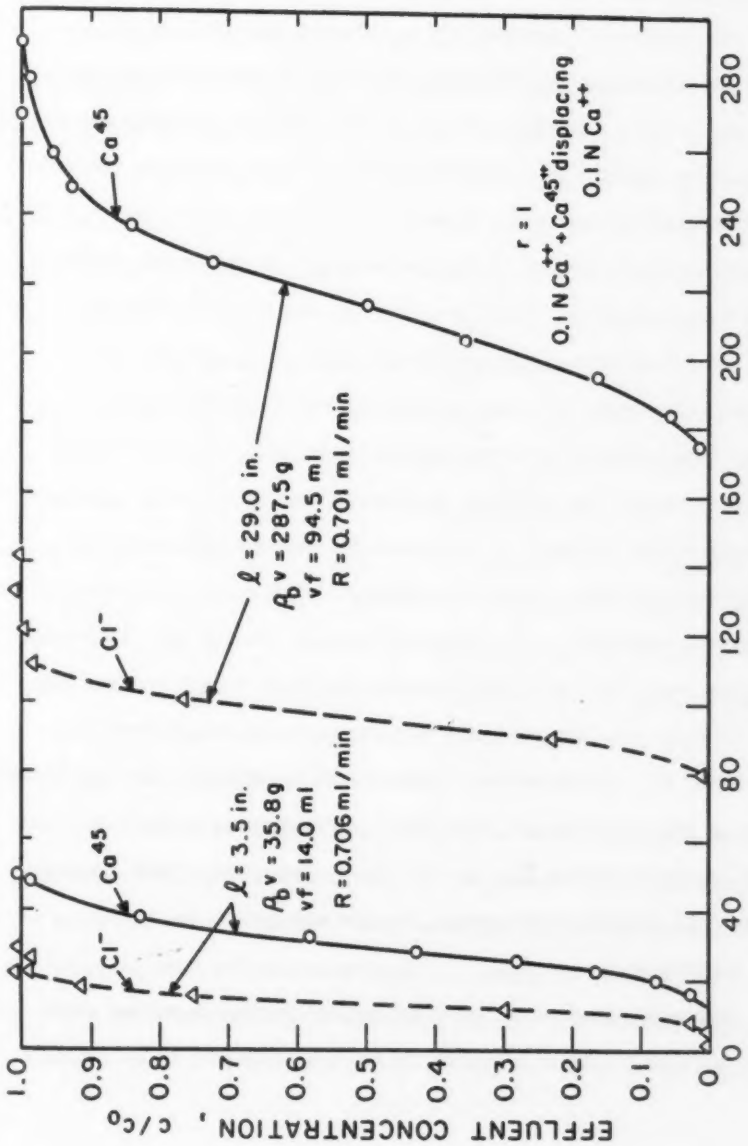

FIG. 7 - EFFECT OF COLUMN LENGTH - ROSECRANS SAND

waste is free of particulates or chemicals forming precipitates when mixed with the soil and ground water. The second condition is the most critical from the standpoint of public health and public relations and admittedly will be extremely difficult if not impossible to meet under all circumstances. However, it is believed that the geology of many areas when examined together with the location of cities and water supplies, may offer a disposal resource about which the engineer may design a free-discharge ground disposal system with the assurance that the wastes will not subsequently constitute a hazard to health or in any way impair the benificial uses of ground or surface waters. To enable the designer to provide such assurance, it is necessary for him to understand the hydraulic and ion-exchange phenomena determining the direction and maximum rate of movement of trace concentrations of radioisotopes.

This paper presents several theories describing quantitatively hydraulic dispersion, ion-exchange equilibria, and ion-exchange kinetics as they apply to the movement of radioisotopes through natural porous media. Laboratory studies have been conducted with radio-strontium and several natural exchangers to determine the applicability and limitations of these theories. The laboratory results obviously do not conclusively establish that the maximum rate of strontium movement can be readily predicted under all circumstances. However, it is believed that the theories of dispersion and ion-exchange, when used in conjunction with field-scale tests, will serve to reduce greatly the uncertainties of ground disposal operations. The salient experimental results are summarized in the following paragraphs.

1. Hydraulic dispersion, or longitudinal mixing in porous media can be treated mathematically as a random phenomenon analagous to molecular

counter diffusion. A solution has been presented that closely depicts the breakthrough of non-exchanging hydraulic tracers. Dispersion, as measured by the slope of the breakthrough curve, was shown to be dependent on the medium and the distance traveled, but essentially independent of velocity. By considering hydraulic dispersion, it becomes possible to estimate the maximum rate of travel of those components of a waste not entering into exchange reactions with the medium.

2. The exchange capacities of connate sands of widely different origins ranged from 0.3 to 13.0 meq per 100 g. as determined by the use of calcium ion traced with Ca^{45}. Generally, these results were in good agreement with those obtained by the ammonium acetate method.

3. The strontium-calcium equilibrium constants for the various media ranged from 0.98 to 1.68, averaging 1.33. Although the media examined were of widely different origins, the relative preference for strontium and calcium was very nearly constant and, with one exception, favored strontium. Low pH was observed to reduce both the exchange capacity for strontium and calcium and the strontium-calcium equilibrium constant. Sodium had a similar effect on the uptake of calcium and strontium. However, the calcium-sodium equilibrium constant was found to be 5.3, indicating a considerable preference for calcium and presumably strontium.

4. The diffuseness or dispersion of a cation front, as the result of exchange reactions, may be far greater than that attributable to hydraulic effects alone. Exchange reactions involving favorable equilibria, such as strontium replacing sodium or calcium, tend to produce relatively steep breakthrough curves, i.e. little dispersion. However, the rate-limiting effects of film and particle diffusion, when

coupled with appreciable flow velocities, cause a high degree of front dispersion. This phenomenon is of practical significance since it increases the maximum rate of waste travel in comparison to the average rate and serves to reduce the effective storage capacity of a formation.

REFERENCES

1. Rifai, M. N. E., Kaufman, W. J., and Todd, D. K., Dispersion Phenomena in Laminar Flow Through Porous Media. Progress Report No. 2, Sanitary Engineering Research Laboratory, University of California, July 1, 1956.

2. Krone, R. B., and Orlob., G. T., Movement of Coliform Bacteria Through Porous Media, Final Report, Sanitary Engineering Research Laboratory, University of California, November 30, 1956.

3. Thomas, H. C., Heterogeneous Ion Exchange in a Flowing System, Jour. Am. Chem. Soc., 66, 1664 (1944).

4. Thomas, H. C., Chromatography; a Problem in Kinetics. Ann. N. Y. Acad. Sci., 49, 161 (1948).

5. Hiester, N. K., and Vermeulen, T., Saturation Performance of Ion-Exchange and Adsorption Columns. Chem. Eng. Progress, 48, No. 10, 505-516 (1952).

6. Hiester, N. K., Radding, S. B., Nelson, R. L., and Vermeulen, T., Interpretation and Correlation of Ion-Exchange Column Performance Under Nonlinear Equilibria. Am. Inst. Chem. Eng., 2, No. 3, 404-411 (1956).

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MOVEMENT OF RADIONUCLIDES THROUGH SOILS AT JACKASS FLATS

(By Los Alamos Scientific Laboratory)

In addition to the work on retention of radionuclides in soils reported in another paper ("Soil Adsorption of Radioactive Wastes at Los Alamos") an additional project on soils retention is now in progress. This program is in conjunction with Project Rover, the nuclear-propelled rocket program at the Nevada test site.

The reactor, after having been exhausted, will be brought back to the MAD (materials assembly and disassembly) building for further test purposes. It is expected that rather large quantities of waste water will be produced in washing down operations. This water will be disposed of in a tile field very similar to a septic tank field.

In order to obtain information on the movement and retention of radionuclide in soils at rather extensive program has been set up. Caissons have been installed between two tile lines in this field and horizontal holes have been drilled so as to intercept the waste water as it percolates through the soil. Porous ceramic cups will be inserted in these holes and a vacuum applied to obtain samples of the percolated water. These samples will be collected at different depths and analyzed for the various nuclides to determine which nuclides are held and which pass on through this particular type of soil.

Soils samples have been obtained from various locations and depths in this area and ion exchange capacities have been determined by radiochemical methods. It is hoped to try to correlate laboratory results with field determinations. In other work performed at Los Alamos (1) it has been shown that the results of testing soil columns in the laboratory do not always agree with results obtained under field conditions so it is deemed advisable to do this work on a full field scale.

In addition to the work described above several other holes have been drilled in the area for the purpose of soil moisture determinations to compute movement of water through the soils. In addition to this, radioactivity determinations will be made in these test holes both before and after the waste waters are admitted to the tile field.

BIBLIOGRAPHY

1. Fowler, Eric B., and Christenson, C. W., "The Effect of Varied Concentrations of Soil Calcium on the Uptake of Sr^{90} by Grass, Alfalfa and Lettuce." Paper presented at the 133d national meeting of the American Chemical Society at San Francisco, April 1958.

INDUSTRIAL WASTES

Soil Adsorption of Radioactive Wastes at Los Alamos

(By C. W. Christenson, Eric B. Fowler, George L. Johnson, Elgin H. Rex, and Felix A. Virgil, Health Division, Los Alamos Scientific Laboratory, University of California, Los Alamos, N. Mex.)

The disposal of radioactive wastes by discharge to the ground has been practiced at Oak Ridge (1), Hanford (2), and Savannah River (3). During the early years of operation at Los Alamos, N. Mex., all wastes were discharged to seepage pits or to canyons. About six years ago this practice was stopped and chemical precipitation treatment plants (4) were installed. The areas receiving these plutonium-bearing wastes have been repeatedly monitored since that time, and no appreciable movement of plutonium through the soils has been noted. It has been observed, however, that the concentration of plutonium in the soil of a canyon receiving low-level wastes has progressively moved downstream. This concentration is not high and, although it is measurable, it is still within acceptable tolerance levels. The movement has not been extensive and is confined within the limits of the Los Alamos Project. Because there was some movement, it was deemed advisable to investigate the travel of plutonium through the local soils under varying conditions. Since there is a possibility that wastes containing strontium-90 and cesium-137 might be produced by the Laboratory in the near future it was decided to investigate these isotopes as well.

The Pajarito plateau, upon which Los Alamos is located, is underlain by Bandelier tuff erupted from the Jemez volcano during a recent geologic period. The Bandelier tuff has been subdivided into three member units which, from youngest to oldest, are the Tshirege, Otowi, and Guaje members. The Tshirege member forms the massive pinkish-orange colored cliffs that are the canyon walls in the Los Alamos area. It ranges in thickness from 100 to 200 ft near the Rio Grande to about 1,000 ft under the town site and shows general, irregular joining and locally well-developed columnar joints. The Otowi and Guaje members, ranging in thickness up to about 200 and 50 ft, respectively, underlie the Tshirege throughout most of the plateau and are best exposed in the lower reaches of the canyons which are cut into the plateau.

The Tshirege member of the Bandelier tuff is composed mainly of welded tuff resulting from two or three ash flow eruptions from the Jemez volcano. The rocks of the Tshirege member generally are porous and friable but only slightly permeable. The permeability varies from 1 to 5 gpd/sq ft under one foot head. The ion exchange capacity for the Tshirege member, which was the tuff selected for this study, varies from 0.5 to 3 millequivalents per 100 grams. The Otowi member is a single thick pumice flow with some ash-fall and water-washed debris at the top, in some locations. The Guaje member consists of massive unconsolidated pumice.

METHODS

Cylindrical cores of tuff about 4¾ in. in diameter and varying in length from 4 to 18 in. were cut from unweathered rock with a core drill. The cores were sealed in a neoprene jacket which extended 3 in. above the upper surface of the core. A 4-in. lucite tube was inserted in the open jacket and served as a reservoir for the applied spike solution. Solutions of the respective nuclides were prepared so that 1×10^6 cpm/l were obtained. The flow of solution was controlled by adjusting the length of a tube attached to the neck of one-gallon jugs which contained the various spikes. Flow was regulated by adjusting the head so that 100 to 200 ml/hr of effluent would be collected in a glass dressing jar equipped with a delivery spout and delivered to a second gallon jug. The arrangement is shown in Figure 1. One of the set-ups is shown to use a polyethylene jug and receiving reservoir. The use of this material was necessitated by the determination of silicon, since it was felt this element might have some bearing on the retention or release of the various nuclides.

Samples were collected at 24-hr intervals or as required and the volumes recorded. At the time of sample collection 1 ml of each sample was plated on a stainless steel planchet, dried, and counted in an alpha or beta counter as required; gamma counts were determined on a 10-ml sample of the effluent. With strontium solutions, in many cases, original plates were counted two weeks later to determine the growth of yttrium. In the case of those effluents containing a mixed spike, radiochemical separations were made.

When increasing activity of the effluent indicated breakthrough of the nuclide, the core was dismantled, dried, and autoradiographs made to determine the distribution of the nuclide with the core. With some cores the application of the nuclide was stopped and leach solutions of various cations were applied to the core.

Determinations of pH, nitrate, calcium, sodium, alkalinity, and silicon content were made according to "Standard Methods" (5).

The weight of radioactive isotopes used in a study of this type is extremely small. For example, the drinking water tolerance for plutonium is 1.5×10^{-6} μc/ml which amounts to about 20 parts per trillion and in the case of Sr^{90} the figure is about 50 parts per quadrillion. At these extremely low concentrations, the chemistry of the various elements sometimes does not follow accepted patterns and ordinary ion exchange phenomena do not always pertain to the particular study. The removals are rather efficient, however, and it is possible, by passing a cesium spiked solution through a tuff core to reduce the concentration from 2×10^{-4} mg/l to 2×10^{-11} mg/l. It is obvious from this that the concentration and nature of the stable ionic components of the water will be the determining factors in the ability of tuff, or any soil, to retain radionuclides.

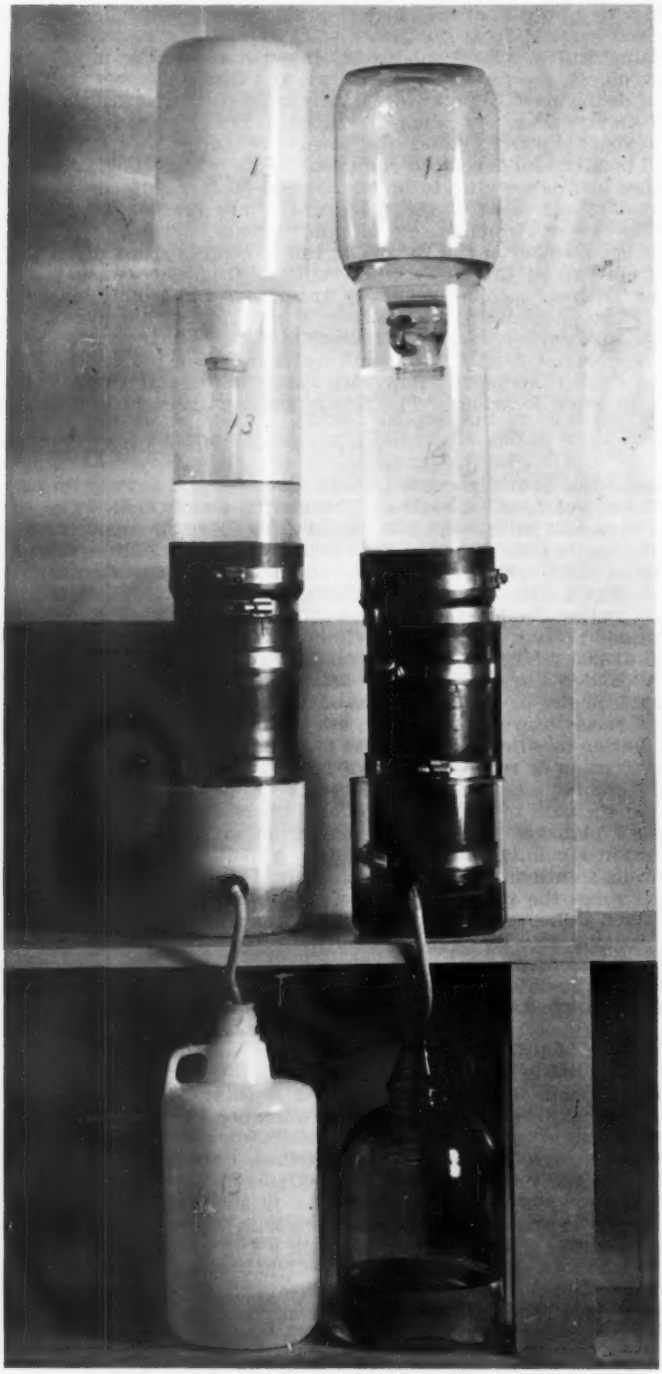

FIGURE 1.—Laboratory apparatus.

RESULTS

Pu^{239} Cores

Seven cores of varying length were fed water spiked with 1×10^6 cpm/l of Pu^{239} as $Pu(NO_3)_4$. The amount of water fed varied from 100 to 380 l and the time of the test varied from two to six months. In every case the retention of the plutonium was in excess of 96 percent. The spike was added to tap and distilled water and there was no apparent difference between the two. An analysis of Los Alamos tap water is shown in Table I. In the case of the core receiving 380 l of water this amounts to an application of 380×10^6 cpm and represents about 1,520 in. of water or some 90 yr of Los Alamos rainfall.

TABLE I.—*Analysis of Los Alamos tap water*

Constituent	Concentration (ppm)	Constituent	Concentration (ppm)
Phen. alk	0	Chloride	5.0
M.O. alk	116.0	Fluoride	1.2
Total hardness	24.0	Nitrate nitrogen	1.0
Calcium	9.0	Sulfate	4.5
Magnesium	0.4	Silica	35.0
Sodium	51.0	Total solids	214.0

Plutonium, because of its high atomic weight and valence, can be expected to be tightly bound on any ion exchange material and replace many other ions. The ion exchange capacity of the tuff cores was exhausted after the passage of only a few liters of tap water, yet the plutonium was retained in a small portion of the core even after several hundred liters had passed through.

Autoradiographs were made by placing photographic film on cores that were cut in half. As can be seen in Figure 2 the activity penetrated to a depth of about 2 in. At this rate it is highly improbable that any plutonium, discharged in this form, would reach the Los Alamos ground water some 1,000 ft below ground surface in the foreseeable future. It should also be noted that there are several "hot" spots (white) in the radiograph which indicate the presence of localized concentrations of high ion exchange material such as montmorillonite clays.

Later attempts were made to leach out the plutonium already adsorbed on the cores by solutions of sodium, calcium, and magnesium in concentrations of 100 ppm as well as a saturated solution of carbon dioxide. None of these solutions removed appreciable amounts of plutonium.

Since this study was directed toward basic work very little effort was expended on actual wastes or complexing agents. It has been pointed out that plutonium complexes quite easily and in this condition is removed from solution only with great difficulty (4). It is to be expected that, under these conditions, it would not be retained by soils.

Dilutions of plutonium salts in basic or slightly acid solutions show a tendency to form polymerized, hydrated molecules which are extremely large (6). These polymerized molecules are entirely too large to enter into an ion exchange reaction and could be expected to pass through almost any type of soil. In addition to this effect other experiments have indicated that complexing agents such as: versene, citric acid, soaps, etc., have an adverse effect on the retention of plutonium in tuff. The data are not complete enough to report on at this time. However, it is known that such agents do interfere with removal of plutonium from liquid wastes by chemical precipitation and they might be expected to show a comparable effect in soils. Experiments on the effect of these agents as well as other ions are in progress.

Cs^{137} Cores

Eight cores of varied length were fed water spiked with 1×10^6 cpm/l of Cs^{137} applied as $CsNO_3$. In addition one core received a spike of 10×10^6 cpm/l. Both distilled and tap water were used as diluents to bring the spikes to the required concentration.

Swope (7) has reported that cesium is not held tightly by the resin, Nalcite HCR. However, she points out further that there is a difference among the various synthetic ion exchangers in their ability to retain cesium. That there is a great difference between synthetic ion exchangers and soils has been borne out by the investigations reported here. It was found that cesium was bound very tightly by the tuff with little regard for other ions present in tap water.

FIGURE 2.—Autoradiograph of tuff core—Pu^{239} studies.

FIGURE 3.—Autoradiograph of tuff core—Cs^{137} studies.

The lowest percentage retention was 99.6 and the highest was 99.99+. Autoradiographs (Figure 3) support the above observations and indicate the cesium to be concentrated in the upper 1 in. of core volume. The amount of water passed through the core varied up to 330 l which represents some 1,300 in. of water added over a period of nearly six months. There was no apparent difference between the tap and distilled water solutions. Later attempts to dislodge the adsorbed cesium by leaching with solutions of sodium, calcium, magnesium, and carbonic acid were futile and the cesium remained stationary (see Table II).

Another investigation in progress, Project Green Thumb has yielded some results which are applicable to the present study. Project Green Thumb is primarily a study of the effect of calcium on the adsorption from spiked soils of Sr^{90} and Cs^{137} by plants. When a spike of these two radionuclides was uniformly distributed through 25 sq ft of soil to a depth of 18 in., Sr^{90} was found to leach from the soil and to appear in the seepage from the bottom of the plots. The amount of Sr^{90} leaching from the soil was proportional to the concentration of calcium applied. The observation did not hold true for Cs^{137} which remained evenly distributed within the soil. The Sr^{90} from a mixed spike applied at the surface migrated downward through the soil but the Cs^{137} remained at the point of application. The results are similar to those observed when a mixed spike of Sr^{90} and Cs^{137} was applied to the surface of a tuff core.

TABLE II.—*Summary of tuff core study results*

Core	Nuclide	Core Length (in.)	Breakthrough Volume (l)	Total Volume Through (l)	Nuclide Removal (%)
1*	Pu^{239}	7.25	—†	331	96.2
2‡	Pu^{239}	7.00	—†	209	96.1
5*	Pu^{239}	6.25	—†	98	96.0
6‡	Pu^{239}	6.25	—†	99	96.7
3‡	Sr^{90}	5.50	30.0	37§	26.4¶
3A‡	Sr^{90}	7.25	50.0	41§	64.0¶
4‡	Sr^{90}	13.75	—†	23	97.0
4A‡	Sr^{90}	13.00	143	63§	88.0¶
7‡	Sr^{90}	6.25	27	22§	65.0¶
8‡	Sr^{90}	12.50	92	65§	73.0¶
13*	Sr^{90}	12.75	400	98§	88.0¶
19‡	Sr^{90}	9.75	20	29§	80.0¶
22*	Sr^{90}	9.75	—†	198	98.0
11‡	Cs^{137}	6.00	—†	62	99.9
14*	Cs^{137}	12.50	—†	330	99.7
16‡	Cs^{137}	6.80	—†	93	99.6
17‡	Cs^{137}	7.00	—†	98	99.9
18‡	Cs^{137}	7.50	—†	261	99.5
23*	Cs^{137}	10.30	—†	240	99.7

*Distilled-water solvent.
†No breakthrough observed.
‡Tap-water solvent.
§Throughput volume after breakthrough.
¶Removal after breakthrough.

The movement of Cs^{137} was further investigated in the laboratory by passing a solution of CS^{137} through a column of soil. When the nuclide, in tap water, was fed to the column it accumulated at the surface as was shown by radioautography. A spike applied to the surface of the soil was not moved by a tap water leach but remained as a thin band at the point of application.

Sr^{90} cores

The investigation of the passage of Sr^{90} [1] through tuff cores proved to be the most interesting of the three nuclides studied. Sr^{90} is not nearly so tightly bound to the tuff core as plutonium or cesium. Furthermore, percolation through the cores demonstrated a method of separating strontium and yttrium. Something over 90 per cent of the activity coming through the core was due to Sr^{90}.

Seven cores were set up using tap and distilled water as the Sr^{90} solvent. An autoradiograph of a typical core after breakthrough is shown in Figure 4. It will

[1] Sr^{90} feed implies an equilibrium mixture of Sr^{90} with its daughter, Y^{90}.

be noted that the strontium has penetrated the full depth of the core. It is also interesting to note the many "hot" spots throughout the core where activity concentrated. This is similar to the phenomenon noted on the autoradiograph for the plutonium core. One other feature to be noted is the density gradation throughout the core indicating a wide variation of ion exchange capacities.

Two typical runs with tap and distilled water are shown in Figure 5. The shape of the curves is quite similar to the typical curves obtained in determining ion exchange capacities by the method of Frysinger and Thomas (8). The first sharp break in the curve is considered to be the breakthrough point. In these particular cores some 80 l were passed through before an appreciable amount of strontium appeared in the effluent. In the case of the tap-water solvent, after 140 l had been applied the concentration of Sr^{90} in the effluent was approximately the same as in the influent. This volume increased to over 200 l when distilled water was used as the solvent.

The slope of the curve for tap water is greater than for distilled water; however, both curves level off at about the same point. The difference in slopes may be explained on the basis of the competition of elements in tap water and of Sr^{90} for the adsorption sites on the adsorbing surfaces, hence a more rapid saturation of the core when tap water is applied. An explanation might be sought for the continued removal of strontium after the core has apparently been saturated with calcium. It is probable that some small amount of calcium is being replaced by strontium; however, the amount of calcium replaced would be so small as to be undetected by the analytical procedures used. It seems reasonable to propose also that within the heterogeneous tuff there exists a wide variety of adsorbents and that some of these might bind the strontium molecule preferentially whereas little or no attraction is exhibited for the calcium molecule. Hence strontium is removed for a period of time after the calcium adsorbing sites have been satisfied. Such a phenomenon is not unknown and is the basis of differential removal of components from biological reaction mixtures by successive treatment with a variety of adsorbing resins. The various synthetic resins show a wide range of preference for different cations so it seems reasonable to assume that the components of tuff could easily demonstrate a similar phenomenon. Unfortunately, there is little, if any, information on ion exchange reactions in extremely low concentrations and much work must yet be done to understand these phenomena.

As noted above, over 90 per cent of the activity in the effluent of the column was due to Sr^{90}. Apparently the relatively high concentration of the divalent ions, calcium and magnesium, does not prevent the adsorption of the trivalent ion, yttrium. The effect of other trivalent ions such as aluminum and iron is being studied.

Mixed Nuclides

In general a waste is a mixture of several nuclides, therefore, the transport of mixed nuclides through tuff cores was investigated. Spikes of both Sr^{90} plus Cs^{137} and Sr^{90} plus Cs^{137} plus Pu^{239} were used as influent at a level of 1,000 cpm/ml each.

One core received a total of 190 l of a Sr^{90}-Cs^{137} spike. Sr^{90} broke through at about 80 l. No Cs^{137} appeared in the effluent after 190 l had passed.

Autoradiographs of the core, Figure 6, indicate the travel of the nuclides. The picture on the left, made with no shielding reflects the concentration of both Sr^{90} and Cs^{137}. The picture on the right was exposed through 1/16 in. of lead and reflects only the location of Cs^{137}. It will be noted that the Cs^{137} was again concentrated in the top 2 in. of the core while the Sr^{90} was spread throughout.

The core treated with Sr^{90}-Cs^{137}-Pu^{239} mixed spike was 18 in. long. A total of 82 l of spiked solution was passed through. The volume of spiked solution was held low to avoid breakthrough in order to obtain a distribution picture of the adsorbed nuclides.

Figure 7 shows the comparison of these radiographs. The picture on the left was made with aluminum foil shielding and reflects the strontium and cesium distribution. The center picture was exposed through lead and reflects the cesium distribution. The picture on the right is a series of photo-micrographs of nuclear track plates placed on the top 3 in. of the core. This type of plate is made by exposing microscope slides coated with photographic emulsion. The alpha particle, because of its relatively large size, does not penetrate the emulsion as is the case with X-rays, gamma rays and beta particles but instead trav els

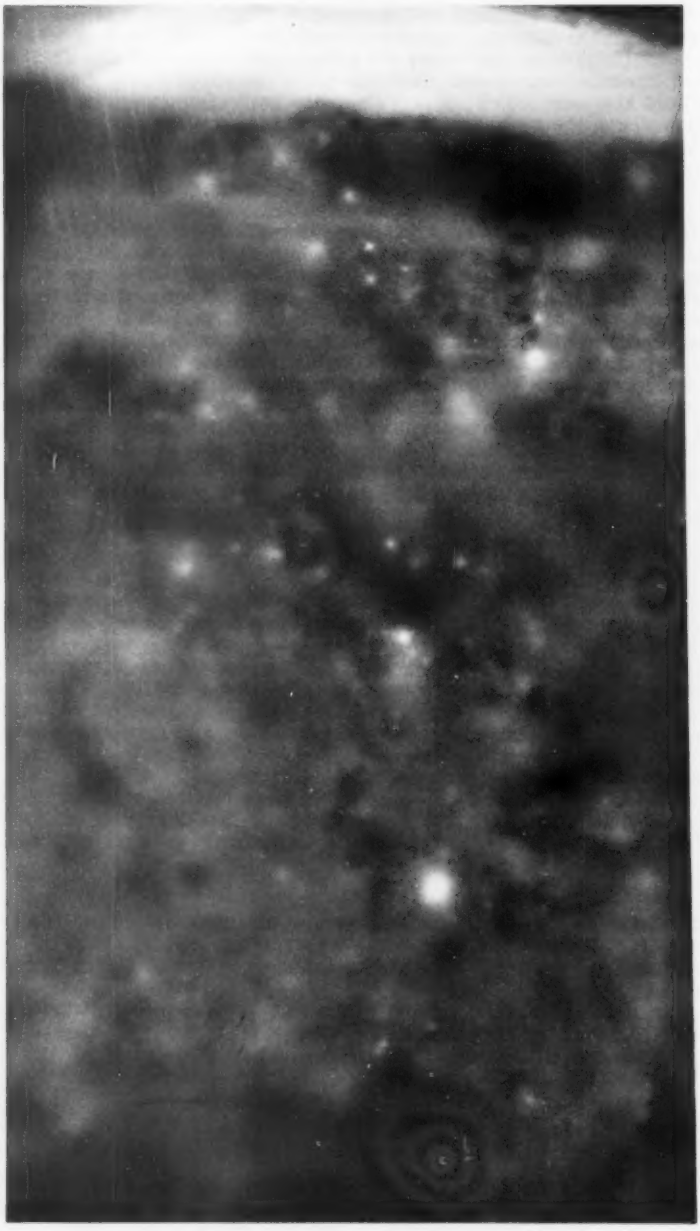

FIGURE 4.—Autoradiograph of tuff core—Sr^{90} studies.

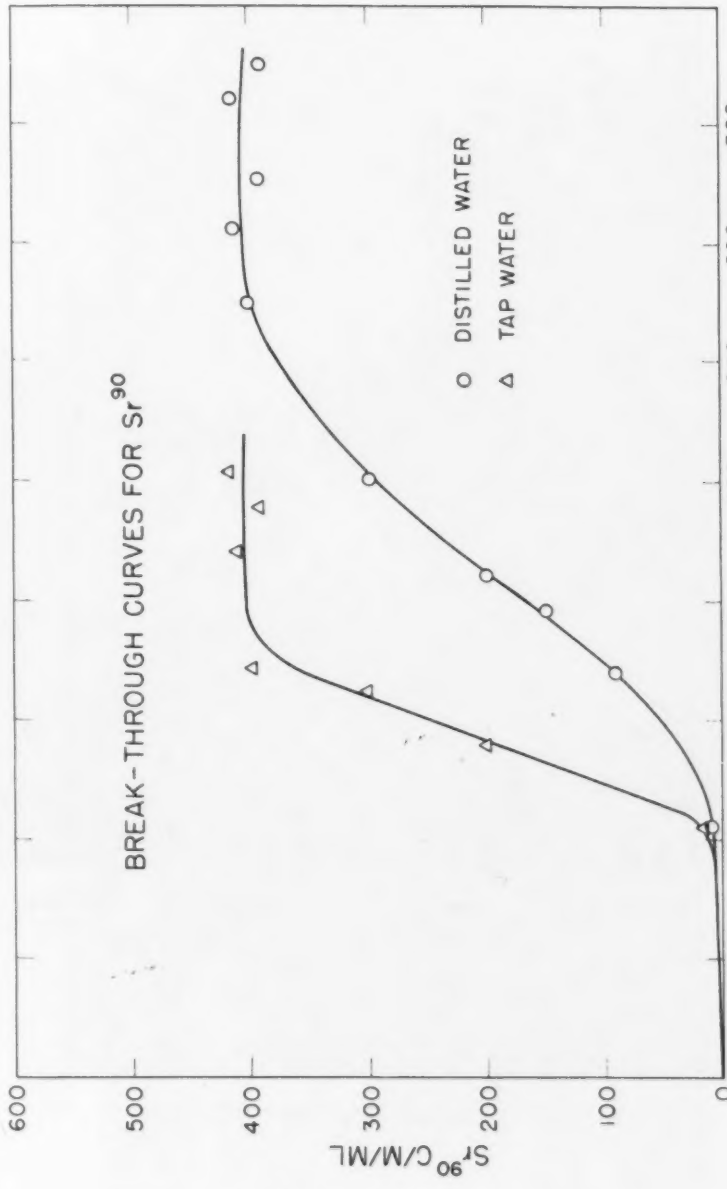

FIGURE 5.—Breakthrough curves for Sr^{90}

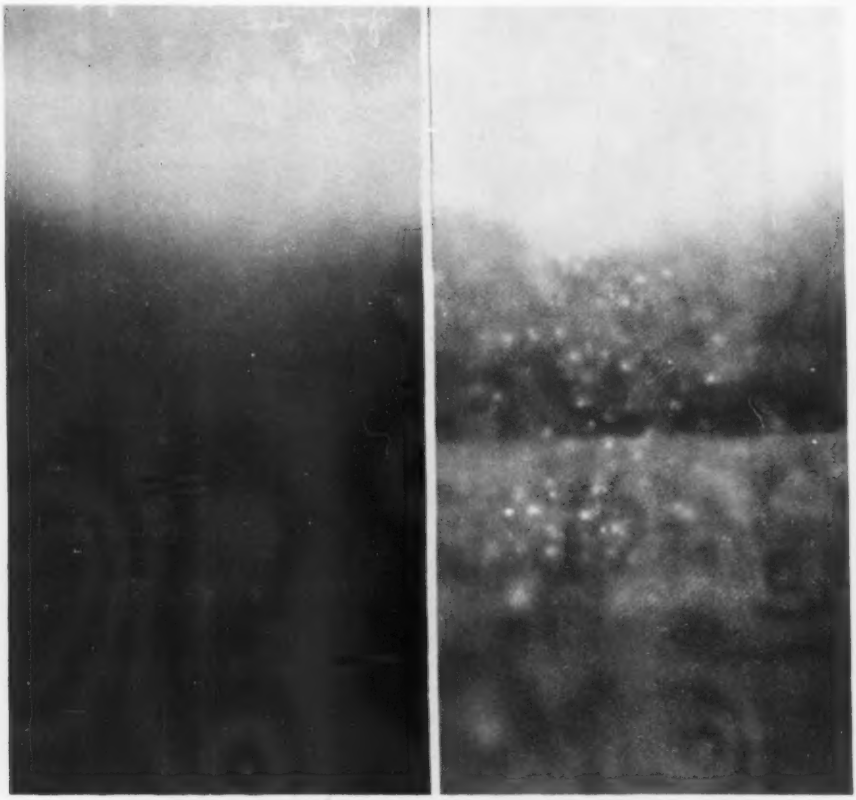

FIGURE 6.—Autoradiographs of tuff core which received a mixed solution of Cs^{137} and Sr^{90}. Picture on left unshielded; picture on right lead shielded.

FIGURE 7.—Autoradiographs of tuff core which has received a mixed solution of Pu^{239}, Cc^{137}, and Sr^{90}. Picture above aluminum shielded; picture on p. 1266 lead shielded. Picture on p. 1267 is alpha track.

FIGURE 7—cont.

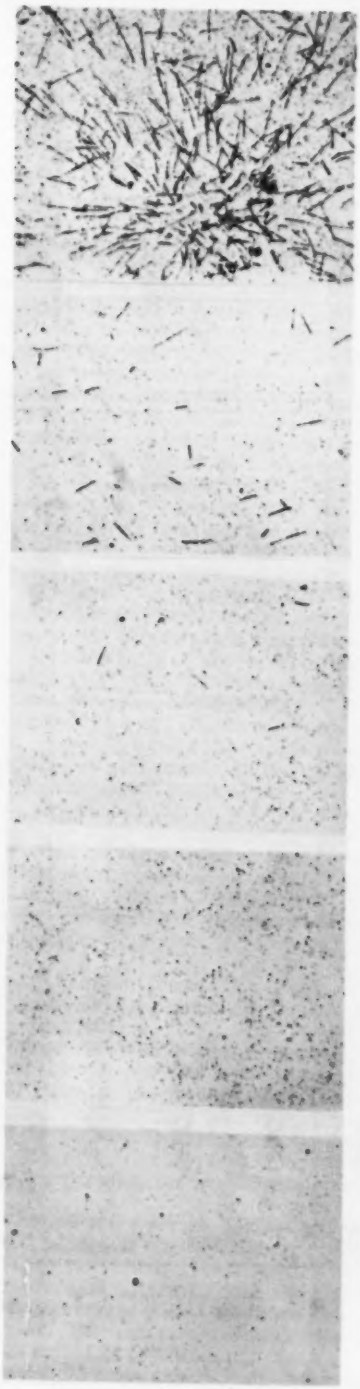

FIGURE 7—cont.

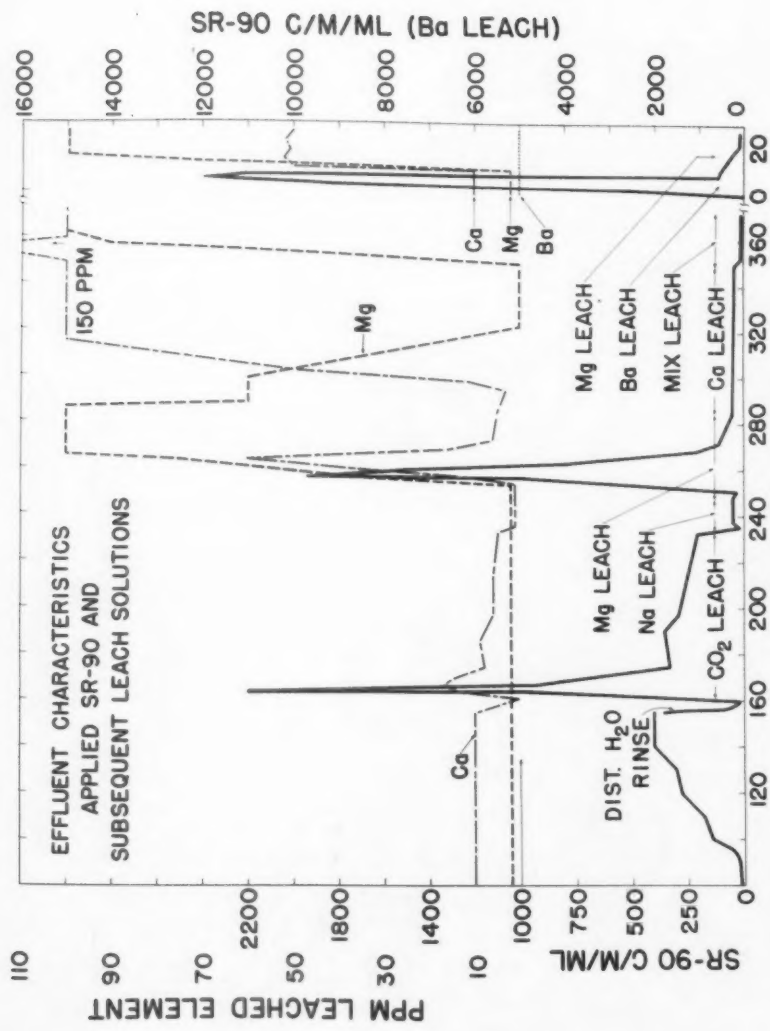

FIGURE 8.—Effects of leach solutions on tuff core—Sr^{90} studies.

along the emulsion leaving a track. A photomicrograph is then taken of the exposure to locate the alpha particle. The magnification of a typical "sunburst" shown in Figure 7 is 400×. From Figure 7 it will be noted again that cesium is located at the top, plutonium travels somewhat further, and the strontium penetrated to a depth of nearly 10 in.

Leaching studies

Early in this investigation it was observed that Sr^{90} in tap water showed a different rate of movement in the core from that observed for the radio-nuclide in distilled water. In some instances there were marked differences in rates of movement. It was theorized that certain elements in the tap water might be competing with the Sr^{90} molecules for position at the site of adsorption. The theory was further investigated by leaching cores which had previously received Sr^{90} up to the point of breakthrough. Referring to Figure 8, it will be noted that the first portion of the curve represents the application of the radionuclide in tap water to the core. This portion is typical of other curves obtained in the study except that it is foreshortened. The maximum level (flat portion) of the curve is followed by a rapid decrease in the release of nuclide as distilled water is applied to the core. This decrease has been observed when other similarly treated cores have been leached with distilled water.

Of interest is the increased amount of Sr^{90} released by a solution of H_2CO_3 prepared by saturation of distilled water with CO_2. It was noted that the released radioactivity was about 95 percent Sr^{90} as was the case with the adsorption studies. Although H_2CO_3 was applied at a continuous rate to a total of 72 l, a sharp decline occurred in released counts after a small increment of leach solution had passed through the core. A similar pattern has been noted with all leach solutions employed. It is possible that the radionuclide is bound to different tuff components with different binding energies and after the weakly bound Sr^{90} has been released, no further leaching occurs until a more rigorous treatment is employed. Concurrently there is a release of calcium from the core and its concentration peaks at about the same point as the peak concentration of strontium. After peak release the concentration curves of calcium and radionuclides are parallel. McHenry *et al.* (9) have shown the effect of pH on the adsorption of Sr^{90} by soil. Since the pH of the carbonic acid feed was about 4.4, it is possible that the leaching of tuff core is, in fact, a pH effect, i.e., a hydrogen regeneration of certain ion exchange components.

Leaching with sodium chloride resulted only in a decrease of calcium and strontium in the effluent. It is to be expected from the lyotropic series that sodium would have little effect on the release of ions higher in the series.

The application of magnesium chloride as a leach resulted in a rapid rise and equally rapid fall in the concentration of Sr^{90} released to the effluent. Magnesium would appear to be about as efficient as carbonic acid in releasing Sr^{90}, however, it is more effective in that it releases bound radionuclides that the latter does not release.

Magnesium also releases calcium from the core in comparatively high concentrations. After the peak has been reached the Ca and Sr^{90} concentrations show a parallel decrease.

The application of calcium resulted in little release of radionuclides; in fact the Sr^{90} concentration in the effluent from the core gradually dropped. The magnesium concentration likewise dropped to zero and remained at that level.

A mixed leach of calcium, sodium, and magnesium had no appreciable effect on the release of Sr^{90} from the core. The concentration of magnesium in the effluent rose rapidly to 100 ppm, the applied concentration, and remained at that level. The increased concentration to 150 ppm in the effluent is real but difficult to explain.

Due to its position in the lyotropic series, barium should be extremely efficient in the replacement of Sr^{90} adsorbed on an exchange medium. The application of barium chloride to a core previously receiving Sr^{90} resulted in the release of the radionuclide at above 12,000 cpm/ml (note the different scale for barium leach in Figure 8). This release is about 12 times the concentration of radionuclide applied to the core. Barium also released increased concentrations of magnesium and calcium as would be predicted.

Distilled water was added to rinse the barium from the core. This was followed by a leach solution of magnesium chloride resulting in an extensive release of radionuclide. It was expected the release would occur but at a lower value. The result is not explained by data obtained to date.

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The leaching studies to date have shown the important effect of water percolating through soil on the movement of Sr^{90}. It is recognized that the concentrations of leaching ions employed in this investigation are above those which would normally be encountered in nature; however, it is well within the realm of possibility that such concentrations might appear in wastes containing radionuclides. The effect of such concentrations of Sr^{90} in a water table tapped for domestic use is self evident.

DISCUSSION

Certain of the results obtained in this study are not in complete agreement with those of Swope (7) who found that both cesium and hardness broke through resin columns at about the same point. McHenry *et al.* (9) indicate a marked effect of the presence of cesium on the breakthrough of strontium. These studies did not show a similar effect. It is possible that the discrepancies are related to the different exchange properties of the basic adsorbents under study.

Orcutt *et al.* (10) have developed excellent expressions for dispersion and exchange phenomena applicable to radionuclides as they move through soils. Whether nuclides in low concentrations that are amenable to soil disposal will follow accepted physical laws is not known. Thomas (11) has stated that it remains to be proved that elements at concentrations of 10^{-7} M follow classical chemistry or the accepted physical laws of ion exchange. It is possible that a demonstration of the applicability of the mathematical treatment of Orcutt *et al.* (10) to solutions where concentrations of solute approach 10^{-7} M will indicate the nature of their chemistry.

It has been demonstrated that the tuff local to Los Alamos has a rather high capacity for the retention of various nuclides. This is especially notable since this particular material has an ion exchange capacity which is about as low as any to be found in nature. Cs^{137} is apparently very tightly bound to the tuff and resists leaching by any of the common agents. Pu^{239} likewise is readily retained by the tuff and from actual experinece at Los Alamos, plutonium in wastes discharged into the ground appear to remain at the point of discharge. However, from what is known about the chemistry of plutonium, it is entirely possible that this nuclide could be released at some future time by inadvertent discharge of solutions such as versene in the same area. Work on this phase is being conducted at Los Alamos.

Sr^{90} is not retained by the tuff nearly so well as cesium and plutonium and it is much more easily released. It is becoming increasingly apparent that its fixation poses a most important problem, and it remains the controlling isotope in the disposal of radioactive wastes. Disposal of this isotope to soils is to be undertaken with extreme caution and only with foreknowledge of the nature of the soil and its capacity for the ions known to be present in the waste. Because Sr^{90} can be leached by other ions, a disposal area receiving this isotope must be closely guarded so that no other wastes will be discharged which might contain concentrations of ions sufficient to dislodge the already adsorbed nuclide.

ACKNOWLEDGMENT

The authors wish to express appreciation to Julia Marie Wellnitz for the autoradiotography entailed in this paper.

REFERENCES

(1) Straub, C. P., "Recent Developments in the Treatment of Atomic Wastes." *Jour. San. Eng. Div., Amer. Soc. Civil Engrs.*, 83, SA3, 1275 (1957).

(2) Thomlinson, R. E., 5th Atomic Energy Industry Conference, Chemical Processing Waste Disposal Study, Roundtable Discussion, Philadelphia, Pa. (Mar. 15, 1957).

(3) Clark, J. R., and Pohl, H. A., "Sanitary Engineering Aspects of the Atomic Energy Industry." A Seminar Report, TID-7517 (Part 1A), pp. 162–169 (Dec. 1955).

(4) Christenson, C. W., *et al.*, "Removal of Plutonium from Laboratory Wastes." *Ind. and Eng. Chem.*, 43, 7, 1509 (July 1951).

(5) "Standard Methods for the Examination of Water, Sewage, and Industrial Wastes." 10th Ed., Amer. Pub. Health Assn., New York, N. Y. (1955).

(6) Seaborg and Katz, National Nuclear Energy Series, IV-14A, "The Actinide Elements." P. 318, McGraw-Hill Book Co., Inc., New York, N. Y. (1954).

(7) Swope, G. H., "Ion Exchange Technology." Pp. 458–520, Nachod and Schubert, Academic Press Inc., New York, N. Y. (1956).
(8) Frysinger, G., and Thomas, H. C., "Clays and Clay Minerals." 395, NAS–NRC, Washington, D. C., pp. 239–245 (1955).
(9) McHenry, J. R., Rhode, D. W., and Rowe, P. P., "Sanitary Engineering Aspects of the Atomic Energy Industry." A Seminar Report, TID-7517 (Part IA), pp. 170–190 (Dec. 1955).
(10) Orcutt, R. G., Rifai, M. N. E., Klein, G., and Kaufman, W. J., "Underground Movement of Radioactive Wastes." THIS JOURNAL, 29, 7, 791 (July 1957.)
(11) Thomas, H. C., Private communication.

Representative HOLIFIELD. Our next speaker is Dr. D. W. Pritchard, Chesapeake Bay Institute, testifying on ocean and tidal estuary disposal.

STATEMENT OF DR. D. W. PRITCHARD,[9] CHESAPEAKE BAY INSTITUTE, THE JOHNS HOPKINS UNIVERSITY

Mr. PRITCHARD. Mr. Chairman and members of the committee, the subject that I will speak about today concerns environmental factors affecting the disposal of radioactive waste materials into tidal estuaries and coastal bodies of water.

The nature and quantity of radioactive wastes which result from industrial use of nuclear power are discussed by other witnesses to this hearing; reference is made here to such matters only for the purpose of placing this presentation in proper perspective.

Under present doctrine, the vast bulk of the unwanted fission products which remain contained in the spent fuel elements after separation from the remaining unused fuel and useful isotopes is contained in storage tanks on land, and hence does not at present constitute a hazard to the coastal environment. Brief mention is made

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[9] Born: October 20, 1922, Santa Ana, Calif.
Education: Grade school and high school, Santa Ana, Calif. B.A. in meteorology, University of California at Los Angeles, 1942. M.S. in oceanography, Scripps Institution of Oceanography, University of California, LaJolla, Calif., 1948. Ph. D. in oceanography, Scripps Institution of Oceanography, University of California, LaJolla, Calif., 1951.
Military service: Weather officer, U.S. Army Air Corps, 1942 to 1946. Assigned duty of forecasting sea and swell for amphibious landing operations in Normandy and in Pacific.
Professional experience: In charge, Current Analysis Section, Scripps Institution of Oceanography, 1946 to 1947. Oceanographer, U.S. Navy Electronics Laboratory, San Diego, Calif., 1947 to 1948. Associate Director, Chesapeake Bay Institute, the Johns Hopkins University, 1949–51. Director, Chesapeake Bay Institute, the Johns Hopkins University, 1951 to present. Consultant, Committee on Tidal Hydraulics Corps of Engineers, U.S. Army, 1954 to present. Consultant, Waterways Experiment Station, Corps of Engineers, U.S. Army, Vicksburg, Miss., 1954 to present. Consultant, Robert A. Taft Sanitary Engineering Center, U.S. Public Health Service, Cincinnati, Ohio—on oceanographic factors affecting outfall disposal of municipal wastes. Consultant, Virginia Electric & Power Co., on limnological problems associated with hydroelectric projects.
Present professional activities: In present position as director, Chesapeake Bay Institute, and chairman, Department of Oceanography of the Johns Hopkins University. In position as consultant to Corps of Engineers, U.S. Army, served in formulating programs, employing the use of hydraulic models, in studying movement and dispersion of contaminants introduced into natural water bodies.
Professional societies: Board of Editors, Journal of Marine Research. Board of Editors, Limnology and Oceanography. Secretary, Section of Oceanography, American Geophysical Union. Past vice president, American Society of Limnology and Oceanography. President, the Johns Hopkins University Chapter of the Society of Sigma Xi. Professional member, American Meteorological Society. Member, American Association for the Advancement of Science.
Committee activities: Member, Subcommittee on Oceanography and Fisheries, Committee on the Biological Effects of Atomic Radiation, National Academy of Sciences. Chairman, Subcommittee on Waste Disposal From Nuclear Powered Ships, Committee on the Biological Effects of Atomic Radiation, National Academy of Sciences. Member, Advisory Council of the Institute of Fisheries Research, University of North Carolina. Member, Committee on Oceanographic Research Vessels, National Science Foundation. Panel member, Radioactive Waste Disposal into the Sea, of the International Atomic Energy Agency, Vienna, Austria. Consultant to Special Advisory Committee to Department of Commerce, the National Academy of Sciences.

later in the presentation to the possibility of this situation being altered. For the present, however, the types of wastes which might be disposed of in coastal waters can be grouped into the following categories:

(1) A dilute, relatively low level waste stream containing a small fraction of the radioactive wastes which remain, in the processing of spent fuel elements, after the major portion of the unused fuel and usable isotopes has been separated from the unwanted wastes, the bulk of which has been concentrated and stored on land. Because of its low concentration and large volume this remaining waste stream is difficult, both technically and economically, to treat further, and it possibly will be directly discharged to the environment, either into the ground or into the sea. The Windscale Works in England is now authorized by the British Government to dispose of over 100,000 curies a year of such wastes into the Irish Sea.

(2) Induced radioactive corrosion products, together with relatively small amounts of fission products, which occur in the primary coolant in a reactor, and in any cleanup system used to maintain the quality of the primary coolant. While the quantities of such wastes are small compared to the fission products contained in the fuel elements, they are nevertheless of considerable importance, since release of at least a portion of these wastes to the environment may be technically or economically difficult to avoid, particularly in the case of a nuclear-powered ship.

(3) Packaged radioactive materials resulting from medical and research use, including discarded isotopes together with glassware and other laboratory equipment which may have become contaminated. Also included in this category are solid materials contaminated during operational testing of reactor systems, or as a result of minor accidents.

The purpose of the research program discussed herein is to determine the environmental factors which will affect the disposal of any of these classes of radioactive wastes into the marine environment, with particular emphasis on harbors, estuaries and coastal waters. Not only is the purposeful introduction of radioactive materials into such environments being studied, but also the accidental introduction which might result from some unforeseen accident to a shore-based reactor, or from a collision involving a nuclear-powered ship. The goal of this research is the prediction of the fate of such wastes after introduction to the marine environment, with particular emphasis on the return routes to man. This information can ultimately be utilized in evaluating the risks to man from disposal of radioactive wastes in the marine environment as compared to the costs and risks which might result from other methods of disposal.

The fate of radioactive material introduced into the marine environment is dependent upon the following considerations:

1. The physical and chemical form in which the material occurs when introduced into and mixed with sea water. This factor greatly affects the subsequent dispersion by physical processes and reconcentration by the biota and bottom materials.

2. Initial mechanical dilution of the wastes by the receiving waters, which will depend upon the manner of introduction. Large initial

mechanical dilution is important in reducing the density difference between the initial contaminated volume and the surrounding receiving waters. This reduction in turn favors subsequent natural dispersion.

3. Advection of the wastes away from the source region by currents, and simultaneous turbulent diffusion, which lead to reduced concentrations of the radioactive components in the water.

4. Uptake of the activity onto suspended silt and bottom sediments, which removes some of the radioactive material from the water, and restricts further dispersion.

5. Concentration of activity by various parts of the biota, including shellfish and finfish important to man as a source of food. Some important fission products and corrosion products are concentrated by certain marine organisms by factors of 100 to 10,000-fold over the concentration of these isotopes in the water.

Research is now in progress on each of these basic phenomena in restricted waterways and coastal waters. The process of turbulent mixing is one of the least understood physical phenomena in the field of oceanography. In the present study, data obtained from the introduction of tracer materials into hydraulic models of estuaries, as well as directly into actual estuaries and coastal regions, are employed in formulating and testing hypotheses and equations describing the mixing processes. Geochemical studies involving the physical and chemical state of the various components of the radioactive wastes when mixed with sea water, together with the processes of uptake of these components by suspended silt and bottom sediment, are being initiated. The concentration of certain components of the radioactive wastes by marine plants and animals is being investigated at several laboratories.

In addition to these basic studies, the specific evaluation of New York Harbor in regard to the dispersion and movement of any radioactive materials which might be purposefully or accidentally introduced there is being pursued. An intensive field program is now underway designed to obtain the pertitnent data on water movements and the distribution of chemical and physical properties of the harbor waters. These data are being processed for use with the best diffusion theories presently available to predict the distribution of radioactivity under various assumed conditions of release of the waste material. The program is being sponsored jointly by the Sanitary Engineering Section, Engineering Development Branch, Division of Reactor Development, AEC, and by the Office of Nuclear Projects, Maritime Administration. The field work is being performed by the U.S. Coast and Geodetic Survey, while analysis of the data and computations of the predicted distributions of activity are the responsibility of the Chesapeake Bay Institute, the Johns Hopkins University.

Another research program involves the classification of harbors and coastal waters according to the major factors influencing the movement and dispersion of contaminants which might be introduced into these marine environments. The purpose of this study is to provide a basis for extrapolating the results of detailed investigations, such as the one being conducted in New York Harbor, to harbors and coastal areas for which only limited data are available.

Man's most intimate contact with the marine environment occurs in harbors, estuaries, and other inshore environments, and on the Continental Shelf. The bulk of the marine products utilized by man is harvested in these areas. The physical process of dispersion of any introduced contaminant within a given marine region and the rate of movement of the contaminated volume to adjacent water bodies vary significantly from one coastal region to another. The sedimentation of radioactive materials onto the bottom, and the biological significance of such sedimentation, will also vary considerably from one marine locale to another. Thus harbors, estuaries, and the waters of the Continental Shelf have both a limited and a nonuniform capacity to receive radioactive wastes.

The capacity of the inshore waters and the waters of the Continental Shelf to receive radioactive wastes is limited in comparison with the deep ocean both from a simple volume standpoint and as a result of the intimate contact of man with these coastal waters. The evaluation of the specific amounts of wastes which may safely be introduced into these environments depends critically upon the rate of exchange of the estuarine, harbor and other inshore waters with the waters of the adjacent open shelf, and also in turn the exchange of shelf waters with waters of the open sea.

On the basis of present knowledge, an evaluation of all the factors involved leads to the conclusion that no significant portion of the relatively large quantities of high-level fission products which will result from the predicted utilization of nuclear power can be safely introduced into coastal waters.

Representative HOLIFIELD. Will you please define the scope of the coastal water in your context there?

Dr. PRITCHARD. Yes, sir; I mean waters out to the edge of the Continental Shelf.

Representative HOLIFIELD. But not beyond the edge of the Continental Shelf?

Dr. PRITCHARD. No. Coastal waters in my definition includes to the edge of the Continental Shelf.

Though present doctrine provides for the containment of the bulk of the fission products, conceivably future advances in technology could result in sufficiently high levels of efficiency in fuel utilization that it would be more economical either to store or dispose of the spent fuel elements directly rather than subjecting them to chemical processing. In the case of direct disposal, the deep ocean is the only marine environment which can be considered as a potential receiver of high-level fission products. Whether such disposal in the deep sea would result in undue risks to man and to man's utilization of the sea cannot be answered on the basis of present oceanographic knowledge. However, the coastal environment can with reasonable confidence be eliminated from such consideration.

Even the relatively low level wastes which might be introduced into coastal waters as a result of operation of shore-based reactors, of nuclear-powered ships, of chemical processing plants, and through the disposal of packaged wastes require careful evaluation of the potential risks to man and to man's utilization of the coastal environment resulting from such possible disposal. The processes of concentration of specific components of the wastes by marine plants and animals,

and subsequent return to man in seafood, results in maximum permissible concentrations of a number of radioisotopes in coastal waters which are considerably less than the published maximum permissible concentrations for drinking water. Thus a conservative, but not unreasonable, estimate of the eating habits of a sample coastal population, together with conservative, but again not unrealistic, estimates of the factors by which commercially important marine organisms concentrate certain radioisotopes from the sea water, results in a computed maximum permissible concentration in coastal waters for several potential corrosion and fission components of low-level wastes from nuclear-powered ships of some one-thousandth the corresponding maximum permissible concentration for these isotopes in drinking water.

It is not the intent of this presentation to contend that inshore and coastal waters have no capacity at all for receiving nuclear waste materials, but rather to point out that even the relatively small total activities involved in certain operational wastes should not be introduced into these waters without careful evaluation of the extent of the limited capacity of the environment to receive them safely.

Despite the fact that considerable further research is necessary on many pertinent environmental factors affecting waste disposal, the Atomic Energy Commission faces immediate waste disposal problems which require the application of existing oceanographic knowledge. The National Academy of Sciences, under two of its existing committees (the Committee on Oceanography and the Committee on the Effects of Atomic Radiation on Oceanography and Fisheries) has established three working panels of marine scientists, each of which is preparing recommendations on specific disposal problems of concern to the AEC.

Two of these working panels are considering the feasibility of establishing designated waste disposal sites to receive packaged low-level wastes on the Continental Shelf and continental borderland of the coast of the United States. One of these working panels, under the chairmanship of Dr. Dayton E. Carritt, of the Johns Hopkins University, is considering this problem for the Atlantic and gulf coasts. The second panel, under the chairmanship of Prof. John Isaacs, of the Scripps Institution of Oceanography, is concerned with the Pacific coast. Both of these groups are evaluating all available knowledge of the physical, chemical, and biological processes in these coastal areas which would influence the possible return to man of any of the radioactive materials which might be released from the packaged wastes.

The third working panel, under the chairmanship of the author of this statement, is concerned with the disposal of radioactive wastes from nuclear-powered ships into the sea. All three groups expect to transmit final reports of their conclusions to the National Academy of Sciences within the next several months.

That completes my oral statement. I have also submitted a longer statement for the record.

Representative HOLIFIELD. Are there any questions of the doctor?

Chairman DURHAM. I gather from your statement, Doctor, that you don't feel it is very safe to use the ocean as a disposal for this radioactive material even though it is low-level waste.

Dr. PRITCHARD. I would put it a different way, sir. I consider that it is unsafe to dispose to this environment without specific evaluation, for the area concerned, of the amount that that area can assimilate. I feel that it would be wrong not to utilize the capacity of this environment to the safe level. I merely wish to point out that even the operational wastes which we have said are a very small fraction of the amount of fission products which will be available and required to be disposed, could affect the environment if introduced into the wrong areas.

Chairman DURHAM. In other words, we had better know what we are doing.

Dr. PRITCHARD. That is exactly it, sir.

Representative HOLIFIELD. Mr. Bates.

Representative BATES. Do you have any comment on the previous presentation relative to the Columbia River?

Dr. PRITCHARD. I believe that the evaluation in regard to the Columbia was carried on in the manner which I outlined here as being desirable. That is, the evaluation of the return routes to man, the fish, of the fish themselves, and hence the evaluation of the capacity of that system which, like coastal regions, would be limited. I am talking about the same type of wastes that are being introduced into the Columbia. That specific environment is being evaluated in terms of its effect on man and on the products of the aquatic environment utilized by man. This is the primary thing I am pleading for, that we do make these evaluations, that we not skimp on the necessary financial and technical obligations of finding out what the environment will accept.

Representative BATES. What would be the factor of the *Nautilus* being in a collision in New York harbor?

Dr. PRITCHARD. First, I should say that vessels such as the *Nautilus* or of the planned *Savannah* or any of the contemplated nuclear vessels planned in this country are designed with extreme safety factors such that the breeching of the containment vessel or of the core itself by a collision would involve speeds and ship sizes which would not occur in harbors. That is, a vessel would have to ram the *Nautilus*—I am more familiar with the *Savannah*—in exactly the right place and the vessel that was doing the colliding would have to be a rather large vessel, of which there are a limited number in the world, and would have to be traveling at a speed in excess of that allowed in harbors, that is something like 18 knots. The ships travel more like 5 to 6 knots in the harbor. So it is what we might call the worst conceivable possibility that such a thing could happen in a harbor. If you want to go to the extreme, if that were to happen in that case, where some completely unforseen thing occurred, a certain fraction of the fission products contained in the fuel elements could be released to the environment. We are attempting to evaluate the process whereby these fission products and corrosion products would be dispersed within the harbor in order to be able to predict or present a basis for a plan whereby certain areas could be closed off, water supplies shut off, and predict the time involved for the natural flushing process to carry the wastes to sea and disperse them over a wider area. If such a very unlikely event occurred, certainly we could not avoid the fact that there would be areas of the

harbor that could not be used for some time. Ultimately the natural process would clean them out.

Representative BATES. It could happen this side of the Continental Shelf.

Dr. PRITCHARD. Yes, it would mean that a certain area may have to be closed to fisheries for a certain length of time.

Representative HOLIFIELD. As far as the general operation of these nuclear submarines, they are pretty much self-contained as far as the discharge of any effluent, radioactive effluent increase concerned, I understand.

Dr. PRITCHARD. It is my understanding that the bulk of the wastes of course is contained in the fuel elements. There is a discharge of a low-level liquid waste, part of the primary coolant at time of warmup. This amounts to a total of perhaps over a year's time of something like 5 curies a year from one ship.

Representative HOLIFIELD. Very low.

Dr. PRITCHARD. Spread over the whole year. Of more significance is the discharge of the resins, the ion exchange resins, that are used in the bypass cleanup system for the primary coolant. Now it is conceivable that these may get to several hundred curies every 60 days or so. For the release of such resins, however, the site of release can be selected, that is, they have spare elements and these can be slurred over the side when the ship is safely into deep water and into regions not utilized for fishing and hence far from man. We have evaluated the rate of dispersal of this type of material in the open ocean and find that it would not be a danger to man.

The return route to man is so far removed that by the time it would reach man's environment it would be near background levels.

Representative HOLIFIELD. Thank you, sir.

Any further questions of Dr. Pritchard?

(Dr. Pritchard's formal statement follows:)

ENVIRONMENTAL FACTORS AFFECTING THE DISPOSAL OF RADIOACTIVE WASTE MATERIALS INTO TIDAL ESTUARIES AND COASTAL BODIES OF WATER

(By D. W. Pritchard, Chesapeake Bay Institute, the Johns Hopkins University)

Introduction:

An unavoidable consequence of the operation of any fission reactor, whether located on land for the production of electric power or as a research tool, or aboard a ship to provide propulsion power, is the production of unwanted radioactive by-products, or wastes. The nature and quantity of such wastes are discussed by other witnesses; reference is made here to such matters only for the purpose of placing this presentation in proper perspective. The discussion of the problem of introduction of radioactive materials into the coastal marine environment is facilitated by classifying nuclear wastes into the following subdivisions.

1. Fission products produced in the fuel elements. These comprise the vast bulk of the waste products and are mainly removed from the reactor with the spent fuel elements at the time of refueling. At present levels of efficiency in fuel utilization, economic considerations require that the spent fuel elements with their contained wastes be processed at a chemical treatment plant. Here the unused uranium fuel, together with certain useful isotope products, is separated from the unwanted radioactive wastes. The greater portion of these wastes is stored in concentrated form in tanks.

Conceivably, advances in technology could result in sufficiently high levels of efficiency in fuel utilization that it would be more economical to dispose of the spent fuel elements directly rather than subjecting them to the chemical processing described above. It is also conceivable that techniques will be developed which would permit economical

transportation of the concentrated radioactive wastes now stored at chemical processing plants. The oceans may be looked toward as a possible receiver of these high level wastes. Also, though admittedly highly improbable in view of the safety factors designed into nuclear power plants, an accident to either a shore based reactor or a nuclear powered ship could result in the release of high level radioactive materials to the sea.

2. A dilute, relatively low level waste stream containing a small fraction of the radioactive wastes, which remains, in the processing of spent fuel elements, after the major portion of the unused fuel and usable isotopes has been separated from the bulk of the unwanted wastes. Because of its low concentration and large volume it is difficult, both technically and economically, to treat, and it may be directly discharged to the environment, either into the ground or into the sea.

3. Induced radioactive corrosion products, together with relatively small amounts of fission products, which will occur in the primary coolant in a reactor, and in any clean-up system used to maintain the quality of the primary coolant. Despite the best possible metallurgical practices, some corrosion and erosion of the metals used in the reactor system will occur. Likewise, the best techniques available cannot insure against some leakage of fission products from the fuel elements to the primary coolant. While the quantities of such wastes are small compared to the fission products contained in the fuel elements, they nevertheless are of considerable importance, since release of at least a portion of these wastes to the environment may be technically or economically difficult to avoid.

4 Packaged radioactive materials resulting from medical and research use, including discarded isotopes together with glassware and other laboratory equipment which may have become contaminated. Also included in this classification are solid materials contaminated during operational testing of reactor systems, or as a result of minor accidents.

The purpose of the research programs discussed herein is to determine the environmental factors which will affect the disposal of any of these classes of radioactive wastes into the marine environment, with particular emphasis on harbors, estuaries and coastal waters. Not only will the purposeful introduction of radioactive materials into such environments be studied, but also the accidental introduction which might result from some unforeseen catastrophe to a shore based reactor, or from a collision involving a nuclear powered ship. The goal of this research is the prediction of the fate of such wastes after introduction to the marine environment, with particular emphasis on the possible return routes to man. This information can ultimately be utilized in evaluating the risks to man from disposal of radioactive wastes in the marine environment as compared to the costs and risks which might result from other methods of disposal.

General Considerations:

The fate of radioactive material introduced into the marine environment is dependent upon the following considerations:

1. The physical and chemical form in which the material occurs at time of introduction, together with any relatively rapid changes in the physical and chemical character of the introduced material which occur when it is brought into contact with sea water. The subsequent dispersion by physical processes and re-concentration by the biota and bottom materials will be greatly affected by the physical and chemical form in which the wastes occur in sea water.

2. Initial mechanical dilution of the wastes by the receiving waters, which will depend upon the manner of introduction. Thus a liquid waste will be subject to greater initial mechanical dilution if introduced as a strong jet into the body of the receiving waters, than if introduced as a gently flowing stream on the surface. Large initial mechanical dilution is important in reducing the density difference between the initial contaminated volume and the surrounding receiving waters. This reduction in turn favors subsequent turbulent diffusion.

3. Advection of the waste material away from the source region, and simultaneous turbulent diffusion, which lead to reduced concentrations of the radioactive components in the water.

4. Uptake of the activity onto suspended silt and bottom sediments, which removes some of the radioactive materials from the water, and restricts further dispersion. In deep water such removal would be favorable since material incorporated with the bottom sediments there would be unlikely to return to man's environment. In shallow coastal areas containing bottom living shellfish and bottom feeding commercial fin fish, concentration of radioactivity on the bottom may be unfavorable

since these detritus and filter feeders may further concentrate the activity from the bottom material.

5. Concentration of activity by various parts of the biota, including shellfish and fin fish important to man as a source of food. Some important fission products and corrosion products are concentrated by marine organisms by factors of 100 to 10,000 over the concentrations of these isotopes in the water.

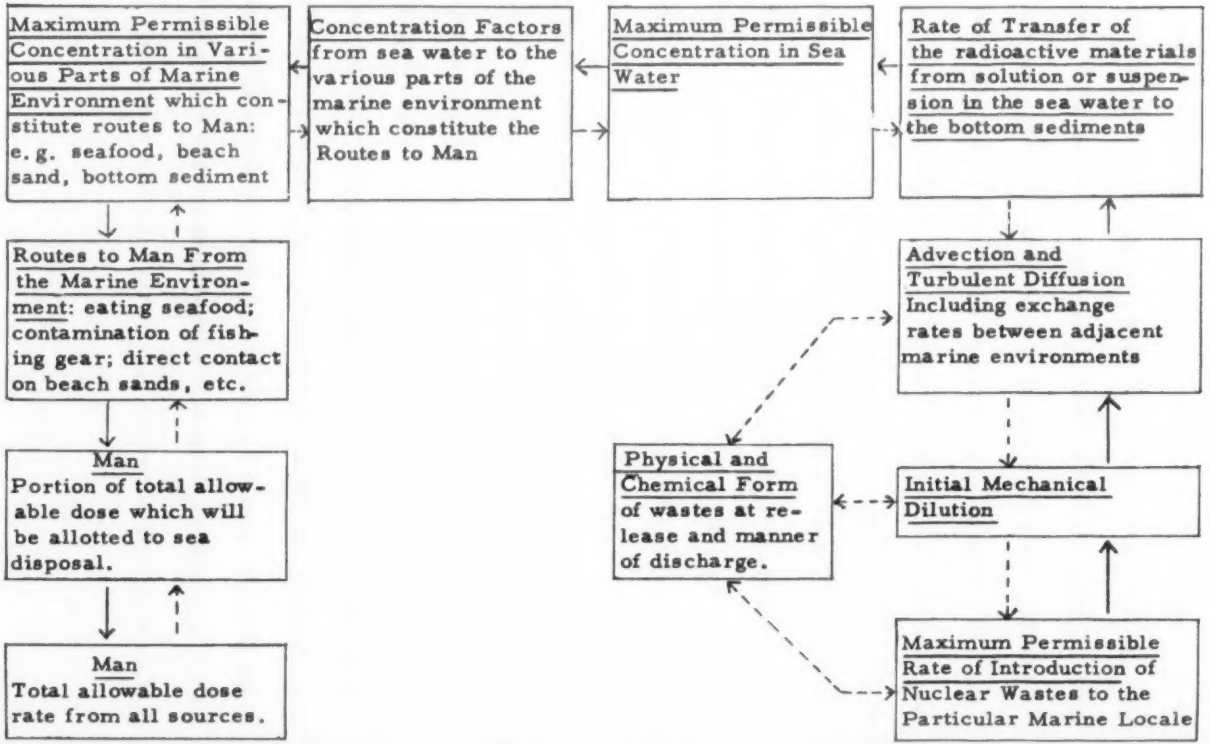
The evaluation of the suitability of any particular marine locality as a receiver of nuclear wastes ideally involves the precise, step by step consideration of all factors affecting the possible return of radioactive material to man. The general procedure is the same whether the evaluation concerns (a) the selection of suitable disposal areas for packaged wastes; (b) the selection of the position of an outfall discharging low level liquid effluent from a chemical processing plant; (c) the consideration of the suitability of a given harbor or harbor approach to receive low level liquid wastes from nuclear powered ships; or (d) the determination of the suitability of the mixed layer of the open ocean to receive wastes from the ion exchange resins on nuclear powered ships. Understanding of many of the physical and biological processes involved is, however, far from adequate, and a basic purpose of the research activities discussed here is to provide an adequate foundation for the determination of the capacity of any particular marine locale to receive nuclear waste materials without undue risks to man.

It is useful to outline the considerations which should be made in such an evaluation, since those areas requiring greatest attention in a research program then become evident. Figure 1 presents the step by step procedure. The solid arrows between blocks on the diagram indicate the route taken by the radioactive material in returning to man, while the dashed arrows indicate the reverse course taken in the evaluation. The starting point in the evaluation is Man. In order to make any evaluation of the problem at all, some maximum permissible rate of exposure must be adopted. The usual basis for the selection of such a maximum rate would be the national (or international) published statement of the maximum permissible ingestion rate for the various isotopes, for the general population. At the outset it should be recognized that such a maximum permissible rate of exposure is not the most desirable rate. The latter, where technical and economic feasibility allow, should be as close to zero as possible. Thus in making this evaluation, some real, though admittedly extremely slight, risk to the general public is assumed.

Considerable care should be taken in any evaluation that the potential additive effect of exposure to radiation from various sources is given due consideration. The second step in the evaluation is then a consideration of all sources of radiation exposure to the particular segment of the population which would also be potentially affected by the waste disposal operations. On the basis of such consideration a portion of the total allowable dose is assigned to sea disposal.

Figure 1

Schematic Presentation of the Step by Step Considerations which Should be made in Evaluating the Suitability of Any Marine Locale as a Receiver of Nuclear Wastes


Maximum Permissible Concentration in Various Parts of Marine Environment which constitute routes to Man: e.g. seafood, beach sand, bottom sediment
Concentration Factors from sea water to the various parts of the marine environment which constitute the Routes to Man
Maximum Permissible Concentration in Sea Water
Rate of Transfer of the radioactive materials from solution or suspension in the sea water to the bottom sediments
Routes to Man From the Marine Environment: eating seafood; contamination of fishing gear; direct contact on beach sands, etc.
Advection and Turbulent Diffusion Including exchange rates between adjacent marine environments
Man
Portion of total allowable dose which will be allotted to sea disposal.
Physical and Chemical Form of wastes at release and manner of discharge.
Initial Mechanical Dilution
Man
Total allowable dose rate from all sources.
Maximum Permissible Rate of Introduction of Nuclear Wastes to the Particular Marine Locale

The next step is the consideration of the various routes which the radioactivity can take in reaching man from the marine environment. Here an evaluation of the uses man makes of the marine environment is required. The possible danger of direct radiation, the harvest of seafood, the possible contamination of fishing gear and the possible contamination of beach sand are some of the items which should be considered at this stage of the study.

The determination of the maximum permissible concentrations of the various significant isotopes in those parts of the marine environment (i.e., the sea food, the bottom sediments, and the shore material), which constitute the routes by which radioactivity may return to man from the sea, then follows as the next step in the process. From a consideration of the known factors by which the biota and the sediment concentrate the various radioactive isotopes from the sea water, it is then possible to arrive at the maximum permissible concentration of the various isotopes in the sea water.

The final steps involve evaluating the changes in the concentration and distribution of radioactivity which may be brought about by

(a) exchange between bottom sediment and suspended or dissolved material in sea water;

(b) advection and turbulent diffusion, both within a given marine environment and between adjacent environments;

(c) initial mechanical dilution, influenced by manner of discharge; and

(d) physical and chemical form of the wastes at time of release.

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The end result is an estimate of the maximum rate of introduction of radioactive material which will not exceed the maximum permissible concentration in sea water.

Research Programs:

Research is now in progress on the following subjects pertinent to the question of disposal of radioactive waste products into estuarine and coastal bodies of water:

1. Basic studies of the mechanism of diffusion in restricted waterways and in coastal waters. The process of turbulent mixing is one of the least understood physical phenomena in the field of oceanography. In the present study, data obtained from the introduction of tracer material into hydraulic models of estuaries, as well as directly into actual estuaries and coastal regions, are employed in formulating and in testing hypotheses and equations describing the mixing process.

2. Specific evaluation of New York Harbor in regard to the dispersion and movement of any radioactive materials which might be purposefully or accidently introduced there. An intensive field program is now under way designed to obtain the pertinent data on water movements and the distribution of physical and chemical properties of the harbor waters. These data are being processed for use with the best diffusion theories presently available to predict the distribution of radioactivity under various assumed conditions of release of the waste material. The program is being sponsored jointly by the

Sanitary Engineering Section, Engineering Development Branch, Division of Reactor Development, AEC, and the office of Nuclear Projects, Maritime Administration. The field work is being performed by the U. S. Coast and Geodetic Survey, while analysis of the data and computations of the predicted distributions of activity are the responsibility of the Chesapeake Bay Institute, The Johns Hopkins University. The numerical solution of the complex equations governing the diffusion phenomena will be carried out using high speed electronic computors at the AEC Computing and Applied Mathematics Center, New York University.

3. The classification of harbors and coastal waters according to the major factors influencing the dispersion and movement of contaminants which might be introduced into these marine environments. The purpose of this study is to provide a basis for extrapolating the results of detailed investigations, such as the one being conducted in New York Harbor, to harbors and coastal areas for which only limited data are available.

4. Geochemical studies involving the physical and chemical state in which the various components of the radioactive wastes would occur in sea water, and the processes of uptake of these components by suspended silt and by bottom sediment.

5. The concentration of certain components of the radioactive wastes by marine biota. Present emphasis in this area of research at the Chesapeake Bay Institute is being placed on the uptake

by marine phytoplankton, the first stage of the food chain. Other laboratories, notably the Fish and Wildlife Service Laboratory at Beaufort, N. C., have been concerned with the uptake of radioactive isotopes by shellfish and fin fish. While considerable knowledge in this area is now available, there are certain products of the radioactive corrosion for which no information on metabolic utilization and concentration in the marine biota has yet been obtained.

General Comments on the Capacity of Inshore and Coastal Waters to Receive Radioactive Wastes.

Man's most intimate contact with marine environment occurs in harbors, estuaries, and other inshore environments, and on the continental shelf. The bulk of the marine products utilized by man are harvested in these areas. The physical processes of advection and diffusion which lead to dispersion of any introduced contaminant within a given region and to movement of part of the contaminated volume to adjacent water bodies, vary significantly from one coastal region to another. The sedimentation of radioactive materials onto the bottom and the biological significance of such sedimentation, will also vary considerably from one marine locale to another. Thus harbors, estuaries and the waters of the continental shelf will have both a very limited and a non-uniform capacity to receive radioactive wastes.

The capacity of the inshore waters and the waters of the continental shelf to receive radioactive wastes is limited, in comparison with the deep ocean, from a simple volume standpoint. The evaluation of the specific

amounts of wastes which may be introduced into these environments depends critically upon the rate of exchange of the estuarine, harbor, and other inshore waters with the waters of the adjacent open shelf, and also in turn the exchange of shelf waters with waters of the open sea.

An evaluation of all the factors involved leads to the conclusion that no significant portion of the relatively large quantities of high level fission products which will result from the predicted utilization of nuclear power can be safely introduced into coastal waters. The deep ocean is then the only marine environment which can be considered as a potential receiver of high level fission products. Whether such disposal is technically or economically feasible , or desirable, is a question which can not be answered with complete confidence at present, thoogh existing policy calls for containment of these high level wastes on land. In any case, as pointed out by Revelle et al (1957), considerable oceanographic research will be required to answer the question as to the risks involved in disposal of any appreciable quantity of fission products in the deep sea.

Of more immediate concern is the ability of the inshore environments to receive, without undue risk to man, the various low level wastes originating from the operation of shore based reactors, nuclear ships, chemical processing plants, and disposal of packaged low level wastes. Though the activity of such wastes is quite small compared to that of the bulk of fission products now stored on land, the processes of reconcentration by the marine biota and subsequent return to man in sea food

make even these small amounts of radioactivity potentially dangerous. For this reason the maximum permissible concentration of a number of radio-isotopes in coastal waters is considerably less than the published maximum permissible concentrations for drinking water. The validity of this conclusion is shown by the following general evaluation.

Consider that a given segment of the population receives 50% of its protein requirements from sea food harvested from a specific coastal area. Of the sea food utilized by this population it is further assumed that 50% is from invertebrates (oysters, clams, lobsters, etc.). The remaining 50% originates in the fin fish population, which it is assumed that man consumes in the ratio one part bone to nine parts flesh. A human population which obtained one-half of its protein food from marine sources would eat about 750 grams of fish or marine invertebrates per week per person. Thus in this example it is assumed that each member of the population consumes on the average each week 375 grams of marine invertebrates, about 338 grams of soft flesh of fish and 37 grams of fish skeleton.

The recommended maximum permissible long term rate of ingestion of specific isotopes by the general public has been conveniently expressed in terms of the maximum permissible concentration in drinking water, assuming that an individual drinks some 2200 ml of water each day. If the sea food eaten by the subject population were contaminated with a radioisotope, and if this were the only source of ingestion of the isotope, the maximum permissible concentration in food corresponding

to the mpc in drinking water can be calculated by multiplying the latter by the ratio :

$$\text{water ingested per week} \Big/ \text{food ingested per week.}$$

In this example the above ratio would be

$$\frac{2200 \times 7}{750} \doteq 20$$

Thus the mpc values for sea food for a population which received one-half its protein requirement from this sea food would be about twenty times the mpc values for drinking water.

The population may be exposed to radiation from other sources than through sea food. Ground radiation and atmospheric contamination (as from incinerated low level wastes or venting from gas cooled reactors) are potential alternative sources of exposure. The entire maximum permissible exposure cannot, therefore, be assigned to the sea. It is necessary to decide how much of the maximum permissible exposure should be allocated to the ingestion of marine foods. For the purpose of this calculation an arbitrary value of 20% has been selected. The maximum concentration in sea food would then be about four times the mpc values for drinking water for the general public.

As pointed out previously, the marine organisms will concentrate selected radio-isotopes from the water. If the concentration factor by which food organisms concentrate the isotope in question in their bodies from their environment is known, then the maximum permissible

concentration in the sea water can be calculated from the maximum permissible concentrations in the sea food.

Table 1 gives a list of a number of radio-isotopes which are potential components, originating either as corrosion products or as fission products which have leaked from small imperfections in the fuel elements. Also listed in Table 1 are: (a) the known or estimated concentration factors for marine invertebrates, for the soft parts of fish, and for the bones of fish; (b) the weighted mean concentration factor assuming an ingestion ratio of invertebrates to fish flesh to fish skeleton of 10:9:1; (c) the mpc values for drinking water for the general public as published in Chapter 10, Code of Federal Regulations, Part 20, Revised, 1959; (d) the maximum permissible con centrations for sea food, based upon the assumptions outlined above, which in this case are taken as four times the mpc values for drinking water; (e) the maximum permissible concentrations in coastal waters which provide the sea food eaten by our subject population. These latter values are obtained by dividing the maximum permissible concentration for each isotope in sea food by the weighted mean concentration factor.

The concentration factors which are listed in this table without parentheses are based on experimental evidence. Those enclosed by parentheses are estimates based upon experimental values for similar elements. In the case of tantalum 182 so little is known that no estimate of concentration factors can be made; yet according to the Babcock and

Table 1

Maximum Permissible Concentrations for Selected Radio-isotopes in Sea Food and in Coastal Waters For a Selected Population which obtained one-half its Protein Requirement From Sea Food Harvested From the Coastal Waters. (For other assumptions, see text.)

Isotope	Concentration Factors For Marine Invertebrates	Fish Flesh	Fish Bone	Weighted Mean Concentration Factor	mpc Drinking Water μc/ml	mpc in Sea Food μc/gr	mpc in Coastal Waters μc/ml
Cobalt 60	10^4	(10^3)	(10^3)	5×10^3	3×10^{-5}	1×10^{-4}	2×10^{-8}
Iron 55	10^4	10^3	5×10^3	6×10^3	8×10^{-4}	3×10^{-3}	6×10^{-7}
Iron 59	10^4	10^3	5×10^3	6×10^3	5×10^{-5}	2×10^{-4}	3×10^{-8}
Tantalum 182	?	?	?	?	4×10^{-5}	2×10^{-4}	?
Zinc 65	5×10^3	10^3	10^3	3×10^3	1×10^{-4}	4×10^{-4}	1×10^{-7}
Cesium 137	50	10	(10)	30	2×10^{-5}	8×10^{-5}	3×10^{-6}
Strontium 90	10	1	2×10^2	15	1×10^{-7}	4×10^{-7}	3×10^{-8}
Zirconium 95	2×10^3	(10^2)	(10^2)	10^3	6×10^{-5}	2×10^{-4}	2×10^{-7}
Niobium 95	2×10^2	10^2	(10^2)	150	1×10^{-4}	4×10^{-4}	3×10^{-6}
Ruthenium 106	3×10^3	(10^3)	(10^3)	2×10^3	1×10^{-5}	4×10^{-5}	2×10^{-8}
Cerium 144	8×10^3	12	(10)	4×10^3	1×10^{-5}	4×10^{-5}	1×10^{-8}

Wilcox Co. Report " N. S. Savannah, analysis of operations with regard to waste collection and disposal" (September 1958), this corrosion product will contribute the major portion of the activity in the primary coolant and in the ion exchange resins for this country's first nuclear powered merchant vessel.

Table 1 shows that under the assumed conditions for this particular sample population the maximum permissible concentrations of selected radio-isotopes in coastal waters are less by several orders of magnitude than the mpc values for drinking water. While the assumed eating habits of the sample population are perhaps not representative of the population of this country as a whole, they do represent reasonable estimates of the eating habits of certain segments of the population, the members of which are employed in the fishing industry. Compared to a maritime country such as Japan, these assumed eating habits are conservative estimates of the amount of sea food consumed.

It is not the intent of this presentation to contend that inshore and coastal waters have no capacity at all for receiving nuclear waste materials. Such capacity is sufficiently limited, however, that the low level wastes which would conceivably be introduced into these waters as a normal result of the operation of shore based reactors or of nuclear ships become significant. The ability of any given inshore or coastal locale to receive such wastes depends critically upon the physical processes of advection, diffusion and exchange; upon the geochemical processes of up take by suspended silts and by bottom sediments; upon

the biological processes of uptake by the marine biota; and upon human utilization of the resources of the area in question. It is therefore essential that research on the problems of movement and mixing of inshore and coastal waters, of uptake of radio-isotopes by silt and bottom sediments, and on the concentration of radioactive materials by the marine biota be continued and expanded.

Application of Existing Knowledge to Immediate Waste Disposal Problems in Coastal Areas

Despite the fact that considerable further research is necessary on many of the pertinent environmental factors affecting waste disposal, the Atomic Energy Commission faces immediate waste disposal problems which require the application of existing oceanographic knowledge. The National Academy of Sciences, under its existing Committee on The Effects of Atomic Radiation on Oceanography and Fisheries, has established three working panels, each of which is preparing recommendations on specific disposal problems of concern to the Atomic Energy Commission.

Two of the working panels are considering the feasibility of establishing designated waste disposal sites for the disposal of packaged low level wastes on the continental shelf and continental borderland of the coast of the United States. The first of these working panels, under the chairmanship of Dr. Dayton E. Carritt, of The Johns Hopkins University, is concerned with the possible establishment of disposal sites along the Atlantic and Gulf Coasts. This group has evaluated all available knowledge of the

physical, chemical and biological processes in these coastal areas which would influence the possible return to man of any radioactive wastes introduced into these areas. The final report of this working panel has now been completed and submitted to the National Academy of Sciences for publication.

The second working panel, under the chairmanship of Professor John Isaacs of the Scripps Institution of Oceanography, is considering the problem of package disposal off the Pacific Coast of this country. This group is considering the environmental factors pertinent to the waste disposal problem in their particular coastal region. The conclusions of this group will probably not be available for several months.

The third working panel is concerned with the disposal of radioactive wastes from nuclear powered ships. This group, which is under the chairmanship of the author of this statement, is presently completing its work and expects to submit its final report on the subject by early March.

Because of the lack of adequate knowledge of certain basic phenomena, the conclusions of these working panels must be based on extremely conservative estimates of certain pertinent factors. It is conceivable that the recommended operating procedures may therefore be overly restrictive on the expanding nuclear industry from the standpoint of sea disposal of wastes. However, until adequate knowledge of

the pertinent phenomena is gained, the recommendations of such groups must be considered as the most suitable basis of insuring that any disposal of nuclear wastes into coastal waters not lead to undue risks to man.

References

Revelle, et al (1957) The effects of atomic radiation on oceanography and fisheries, National Academy of Sciences - National Research Council Pub. No. 551, 137 pp.

Babcock and Wilcox Co. Report,"N. S. Savannah, analysis of operations with regard to waste collection and disposal", September, 1958.

Representative HOLIFIELD. Before our next presentation, I have several papers on the subject we have been discussing. I would like to insert them at this point.

RESEARCH NEEDED TO EVALUATE THE EFFECTS OF RADIOACTIVE MATERIAL IN THE MARINE ENVIRONMENT

Material submitted for the Record by Dr. Roger Revelle,
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The National Academy of Sciences' Committee on the Effects of Atomic Radiation on Oceanography and Fisheries, and the National Academy's Committee on Oceanography, have given much consideration over the past three years to the research needed to determine the effects of radioactive materials in the marine environment. Their conclusions are reported at length in Publication No. 551 of the National Academy of Sciences-National Research Council, "The Effects of Atomic Radiation on Oceanography and Fisheries", in the forthcoming report of the Committee on Oceanography, and reports now being prepared by subcommittees on the disposal of radioactive wastes in the Atlantic, Gulf of Mexico and Pacific coastal waters of the United States. The scientists who have been involved in the preparation of these reports include; R.S. Arthur (Scripps Institution of Oceanography), W.Aron (University of Washington), H. Boroughs (Hawaii Marine Laboratory), D. F. Bumpus (Woods Hole Oceanographic Institution), W. V. Burt (University of Oregon), D. E. Carritt (Johns Hopkins University), J. H. Carpenter (Johns Hopkins University), W. A. Chipman (U. S. Bureau of Commercial Fisheries), H. Craig (Scripps Institution of Oceanography), L. R. Donaldson (University of Washington), H. Eckles (U. S. Bureau of Commercial Fisheries), K. O. Emery (University of Southern California), R. H. Fleming (University of Washington), T. R. Folsom (Scripps Institution of Oceanography), R. F. Foster (General Electric Company), E. D. Goldberg (Scripps Institution of Oceanography), G. D. Hanna (California Academy of Sciences), J. H. Harley (U. S. Atomic Energy Commission), B. C. Heezen (Columbia University), J. D. Isaacs (Scripps Institution of Oceanography), A. Joseph (U. S. Atomic Energy Commission), B. Ketchum (Woods Hole Oceanographic Institution), L. A. Krumholz (University of Louisville), F. G. Lowman (University of Washington), D. Pritchard (Johns Hopkins University), R. O. Reid (Texas A&M College), C. E. Renn (Johns Hopkins University), R. Revelle (Scripps Institution of Oceanography), T. R. Rice (U. S. Fish and Wildlife Service), W. E. Ripley (California Division of Fish and Game), G. A. Rounsefell (U. S. Fish and Wildlife Service), M. B. Schaefer (Inter-American Tropical Tuna Commission), A. C. Vine (Woods Hole Oceanographic Institution), M. Waldichuk (Pacific Biological Station, Nanaimo, British Columbia), L. A. Walford (U. S. Bureau of Commercial Fisheries), W. S. Wooster (Scripps Institution of Oceanography).

The members of the National Academy of Sciences' Committee on Oceanography who are reviewing these reports are H. Brown (California Institute of Technology), M. Ewing (Columbia University), C. O'D Iselin (Woods Hole Oceanographic Institution), F. Koczy (University of Miami), S. Pike (Lubec Oceanographic Centre), C. Pittendrigh (Princeton University), R. Revelle (University of California), G. Riley (Yale University), M. B. Schaefer (Inter-American Tropical Tuna Commission), A. Spilhaus (University of Minnesota).

Following is a summary of some of the conclusions and recommendations of this group of scientists.

In disposing of radioactive materials in the sea, two things are desired: (1) isolation of the materials, so that their entry into that part of the sea and its contents used by man is limited, and (2) dispersal of the materials that do enter the domain important to man, to keep the concentrations of radioactive elements at tolerable levels.

In order to determine the quantities of radioactive materials which can safely be introduced into the sea, one must be able to predict the resulting distribution of these materials as a function of space and time. Factors which control this distribution include (1) the physical and chemical state of the pollutant, (2) radioactive decay rates, (3) location of release, (4) dispersal by mixing, (5) dispersal by advection, (6) reaction with suspended materials and sediments, and (7) reaction with the biota.

Coastal and Estuarine Environments

Present state of knowledge

Enough is now known about estuarine environments that gross features of the circulation pattern can be deduced from a knowledge of the net fresh water inflow (which, in case of excess evaporation, may be negative) morphology, tidal flow, and salinity distribution. On the basis of these parameters estuaries can be grouped into representative types. The large scale features of dispersion of an introduced contaminant can be estimated for each of these representative types. However, very little is known about details of water movement and mixing in estuaries. Synoptic observations of current velocity and salinity at a number of points in the estuary, as a function of time, are lacking.

In some coastal areas both the gross distribution of physical and chemical properties, and the general circulation are fairly well known. However, many coastal regions have not been intensively studied, and there is insufficient detailed knowledge of water movement and mixing even in the best studied areas.

At the present time approximately $400,000 per year is being expended on estuarine studies which are directly pertinent to the problem of the physical movement and dispersal of an introduced contaminant. An estimated $100,000 is now being expended in the study of pertinent physical aspects of coastal environments.

Research Program

A number of internal and external factors combine to determine the character of the circulation and mixing in an estuarine and in a coastal environment. Studies of a single estuary, or of a single coastal area, will not suffice to provide general, basic concepts applicable to all inshore environments. However, the present state of knowledge of the physical and chemical hydrography of estuaries is such that classification can be made into characteristic types on the basis of (a) physical structure (i.e. length, width, depth, shape, etc.), (b) the net fresh water inflow (or net water loss due to evaporation exceeding inflow) into the estuary, and (c) the character of the tidal flow in the estuary. It appears likely that coastal environments can be likewise grouped into characteristic types based on a relatively few indicator characteristics. Thus, the required research program must involve detailed studies of a number of representative estuarine and coastal environments, such that the range of environmental factors are adequately covered.

Estuaries

Detailed studies of the circulation and mixing in at least four representative types of estuaries should be conducted. These four types are:

(1) Coastal Plain Estuaries: These estuaries are shallow, elongated indentures on the coast line, having free connection with the open sea, and within which sea water is measurably diluted by land water drainage.

(2) Inverse Estuaries: Embayments in which evaporation exceeds precipitation.

(3) Fiord Type Estuaries: Deep coastal indentures in which fresh water inflow exceeds evaporation.

(4) Bar Built Estuaries: Shallow embayments with restricted connection to the open sea, within which tidal motion is hence small compared to wind induced motion.

Such studies should involve:

(1) Field studies of the time and space distribution of currents, temperature, salinity, and possibly of certain specific chemical components, in sufficient detail so that these physical and chemical properties can be related to such external factors as river inflow, tide, morphology of the estuary, and winds.

(2) Detailed studies of the time and space distribution of tracer materials either introduced into the estuary as normal components of wastes from existing industrial or municipal outfalls, or resulting from a planned experimental release. Such studies would provide information on small scale mixing phenomena in the estuary.

(3) Utilization of hydraulic models of estuaries. Present information

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indicates that large scale mixing phenomena are properly scaled from prototype to model, and hence the long time and gross spatial distribution of a contaminant concentration can be studied in hydraulic models. Comparison of results obtained from studies outlined in (2) above with model studies would provide information on the ability of hydraulic models adequately to scale small scale mixing phenomena.

(4) Development of mathematical models which would allow machine computation of the time-spatial distribution of an introduced contaminant in an estuary. The data required for such mathematical treatments may determine the degree of detail required from the field studies outlined in (1) above.

A requisite part of the research program in the development of suitable recording instruments for remote recording of current velocity, temperature and salinity. Because of the relatively rapid time and space changes in these environmental parameters in the estuary and inshore waters, synoptic observations require either a number of research vessels or equipment which can serve to substitute for vessels. Another essential part of such a program is the utilization of modern data handling and computing techniques and machines.

Coastal Environments

The regime of coastal waters includes the continental shelves, offshore banks, the approaches to the major harbors and the routes of coastal shipping. It extends seaward from the well defined coastline to an ill-defined zone of transition to open ocean conditions. Coastal waters are highly variable both in space and time, making it difficult to generalize about their characteristics. Yet despite the difficulty of developing general principles which would permit prediction of the fate of introduced radioactive materials, the region is of greatest importance because (1) it is the marine region most exploited by man, and (2) it is most accessible to present and potential sources of radioactive wastes.

The physical processes which must be understood in order to predict the distribution of radioactive materials, are vertical and horizontal mixing, and advection (especially the component normal to the coast). These processes are strongly influenced by the presence of the coastal boundary, that is, by the nature of the coastline and bottom topography, and the effects of tidal and longshore currents. It is likely that internal waves and inertia currents also contribute to mixing in the coastal regime. Because of the presence of the boundary, convergence of surface drift with the coast will lead to sinking, and divergence of the surface drift will lead to upwelling. Changes in the coastal climate are reflected in changes in the various mixing and advective processes, so that studies must be carried out over a long enough time to establish the nature of these changes. Knowledge of seasonal changes may show that one season is better than another for disposal purposes.

Although each locality in the coastal region will exhibit its own peculiarities, a real understanding of the various exchange processes can be applied anywhere. Furthermore it is likely that each coastal region can be fitted into a broad classification scheme, as shown in the following table. A number of selected areas, typical of these broad categories, should be studied to evaluate the processes involved. Where possible, regions should be selected where introduction of radioactive materials is likely to occur.

Although a large amount of oceanographic work has been conducted in the coastal waters there are serious deficiencies in areal and seasonal measurements and evaluation of the mixing processes. It is therefore recommended that a coordinated program of investigations be undertaken in the areas listed in the table. Such field programs must be supported by model investigations and theoretical studies as indicated below.

1. Field Studies: Coordinated and comprehensive studies should emphasize the distribution of properties (including their microstructure) and current measurements covering a wide spectrum of scales in space and time. Particular emphasis should be placed on the development of moored and drifting buoys with their necessary instrumentation.

2. Time Studies: In key areas shore stations and moored buoys should be established and maintained to determine the nature of short and long term variations in conditions. Short-term multiple ship surveys should be conducted from time to time to establish the general features of the distribution of properties, and to evaluate the processes at work.

3. Model Studies: Because of the complexity of the coastal waters it is urged that preliminary investigations be undertaken immediately to evaluate the effectiveness of models. Such an approach has proved very successful for harbors and estuaries and for hemispheric systems but has not been attempted for areas of intermediate scale.

4. Theoretical Studies: Without adequate theories to guide the field work and the design of models, it will be impossible to synthesize the data, to develop a coherent understanding of the processes at work or to predict in space and time the processes affecting the disposal of radioactive wastes.

5. Coordination: A large number of international, national, state and independent organizations have interests in various aspects of the oceanography of the coastal waters. Most of them are currently engaged in investigating certain aspects or specific areas of the water adjacent to our coast. They should be encouraged to continue such programs, but unless the entire program is coordinated and expanded it will fall far short of meeting the urgent needs. It is strongly urged that the NAS Committee on Oceanography establish a panel to pursue this matter and the related one of the establishment of data centers to compile and analyze the available data and to issue factual summaries.

COASTAL AREAS AND THEIR CHARACTERISTICS

	Alaska & British Columbia	Central California	Northeast U..S. and Canada	Southeast U. S.	Gulf of Mexico (Texas)
Coastline	Very irregular with deep fiords	straight	Very irregular	Straight with shallow embayments	Straight with shallow embayments
Shelf	Narrow and irregular	Narrow	Wide and irregular	Moderate	Wide
Range of Tide	Large	Moderate	Moderate	Moderate	Small
Tidal Currents	Strong	Small	Strong	Moderate	Weak
Climate	Moderate uniform	Moderate uniform	Large seasonal variations	Moderate uniform	Moderate uniform
Water Budget	Large dilution	Net loss by evaporation	Large dilution	Dilution	Dilution(?)
Permanent Circulation	Weak and variable	Moderate	Weak and variable	Strong	Weak
Stability	Large	Small	?	Large	?
Upwelling	None	Large	None	None	None

Estimate of financial support required

A. Estuarine Physical Studies (for four representative environments)

Salaries and wages - 12 people in each of four representative environments	$288,000
Supplies, expense and indirect costs	144,000
Ship operation	400,000
Instrumentation - remote recording equipment	280,000
Data processing and computing	88,000
Model studies	200,000
	$1,400,000

B. Coastal Physical Studies (for four representative environments)

Salaries and wages - 12 people in each of four representative environments	$288,000
Supplies, expense and indirect costs	144,000
Ship operation	480,000
Instrumentation	280,000
Data processing and computing	88,000
Model studies	120,000
	$1,400,000

The Open Ocean

It is our understanding that all nations now developing power reactors plan to dispose of high-level fuel reprocessing wastes by some form of treatment and long term storage on the land. Within the foreseeable future, however, it is possible that very large quantities of these wastes will be produced by nuclear fission power reactors, and these will present difficult disposal problems, particularly for countries with small land areas and large populations. If these countries also have long sea coasts, with easy access to the deep sea, it may be desireable to dispose of some high level wastes in the deep ocean waters even though at the present time no nation plans to do this.

Significant amounts of radioactivity may also be introduced into the open sea by weapons tests, by accidental sinking of nuclear powered vessels, and by the introduction of medium level wastes from power reactors. In the case of a nuclear war, the relative contamination of the terrestial and marine environments may be a very important consideration in the survival of human populations, as discussed further in Appendix B.

The waters of the open ocean are stratified. The uppermost stratum (within which most of man's marine food harvest is obtained) is a relatively thin layer at the surface, varying in thickness in different places but averaging about 75 meters, where vertical mixing caused by winds is fairly rapid and complete. Below the mixed layers is a zone within which the temperature decreases and the density increases rapidly with depth. This thermocline, or pycnocline, separates the surface mixed layer from the layers of intermediate and deep water, the latter

extending to the bottom, within which there are gentle gradients of decreasing temperature and increasing salinity and density with depth. Vertical movements in the intermediate and deep layers is much slower than in the mixed layers, and horizontal currents are more sluggish. The strong density gradient across the pycnocline acts as a partial barrier between the mixed layer and the lower layers. There is, however, some interchange of both living and non-living elements; indeed the continued existence of some marine resources depends on this interchange.

Radioactive materials introduced into the deep water will be partially isolated from the upper mixed layer for at least several decades and perhaps for several hundred years. During this time there will be a decrease of radioactivity due to decay, and dilution due to dispersion. The depths of the sea are thus the only place in the ocean where we can now be confident that radioactive materials of the order of some tons of fission products a year can be safely deposited.

In order to be able to assess the effects of radioactive materials introduced into the sea, we need to know how these materials, when in solution, will be dispersed throughout the deep waters and the amount of activity that will eventually enter the upper layers of the sea, and the organisms in this part of the ocean of most direct interest to man. The physical oceanographic problems are then to estimate rates of mixing within the deep waters and the rate and character of exchange between the deep water and the surface mixed layer.

Tests of the Stommel theory of the deep circulation in the ocean

The most recent and comprehensive theory of the deep ocean circulation has been developed by H. Stommel of the Woods Hole Oceanographic Institution. According to Stommel's theory the deep and bottom waters of the ocean are carried from the high latitude, near-surface source regions to low latitudes in narrow fast-moving western boundary currents at depths of several thousand meters. At all latitudes lateral mixing occurs between the waters in these currents and the waters of the same density in the central and eastern parts of the ocean. Over most of the ocean the deep waters slowly move upward into the region of the thermocline and the return flow to high latitudes takes place in the upper water layers. Stommel estimates that the total transport in the western boundary currents is of the order of 60 million cubic meters/second or 2×10^{15} m^3/year. Since the volume of the ocean is about 1.4×10^{18} m^3, the deep water of the oceans as a whole would be replaced in a time of the order of 700 years. The average velocity of upward movement at the bottom of the thermocline would be $2 \times 10^{15} / 3.6 \times 10^{14}$ or about 5 meters/year (1.5 cm/day). This is too slow to measure directly.

Direct measurements of the transport in the western boundary currents can be made, however. For example, neutral buoyancy buoys of the type developed by John Swallow of the British National Institution of Oceanography could be used. According to Stommel's theory, two "wiers", or gaging stations, are particularly important:

a. The western north Atlantic off the Grand Banks under the Gulf Stream. This should give a measure of the volume of the North Atlantic deep water entering the deep sea.

b. The western south Pacific in the Tonga-Kermadec region. Measurements here should give a measure of the deep and bottom water flowing into the Pacific.

Detailed zonal profiles of temperature and salinity from the surface to the bottom should also be made at every 10 degrees of latitude in the Pacific and Indian Oceans, in order to give the data for geostrophic calculations of the western boundary currents. Similar profiles are already being made in the Atlantic. These will not only give a check on the existence of the western boundary currents, but by determining the total deep and bottom current transport at different latitudes the amount of water passing upward across the thermocline between sections could be determined.

Estimates of the vertical exchange across the thermocline

As shown by H. Craig of the Scripps Institution of Oceanography, it is clear from elementary considerations of the volumes and surfaces involved that only a part of the Carbon 14 entering the deep sea crosses the air-sea boundary in high latitudes and is transported downward to the deep waters by convection. A larger part must come from mixing across the thermocline in middle and low latitudes. Measurements of the Carbon 14 concentration in near-surface and deep waters of high latitudes are necessary to aid in separating the effect of this mixing across the thermocline from high latitude convection. A very much larger number of measurements of Carbon 14 concentrations than are now available should be made at different depths and locations in the deep sea of middle and low latitudes in order to study both vertical mixing across density surfaces and horizontal isopycnal mixing.

Unfortunately, the long half life of Carbon 14 makes it less useful for this purpose than other radioactive materials that decay more rapidly. Such materials of shorter half life are now present in the upper mixed layer as a result of fallout from weapons tests in the last few years. These materials should slowly mix downward across the thermocline. By successive measurements of the concentration of such relatively long lived fission products as Sr^{90}, Cs^{137}, Pm^{147}, Sm^{151}, Ce^{144}, Zr^{95}, and Nb^{95} in the surface layers and within and below the thermocline, a direct measure of the mixing between the surface and deep waters could be obtained. Such measurements should be made at many widely separated points in the ocean to give an average picture. Preferably only those radionuclides present in ionic form should be used.

Mixing within the deep waters

In waters of intermediate depth (100 - 1500 meters) surrounding the

atolls of the Northern Marshalls, the radioactivity prior to the 1956 weapons tests was about five times natural background (the latter due principally to K 40). It is believed that this radioactivity resulted from fallout of solid particles to the intermediate depths from previous weapons tests. Presumably, the 1956 tests increased this radioactivity. By following the lateral spreading of the intermediate depth material from year to year it should be possible to obtain an estimate of the rate of lateral mixing in the central part of the Pacific Ocean basin.

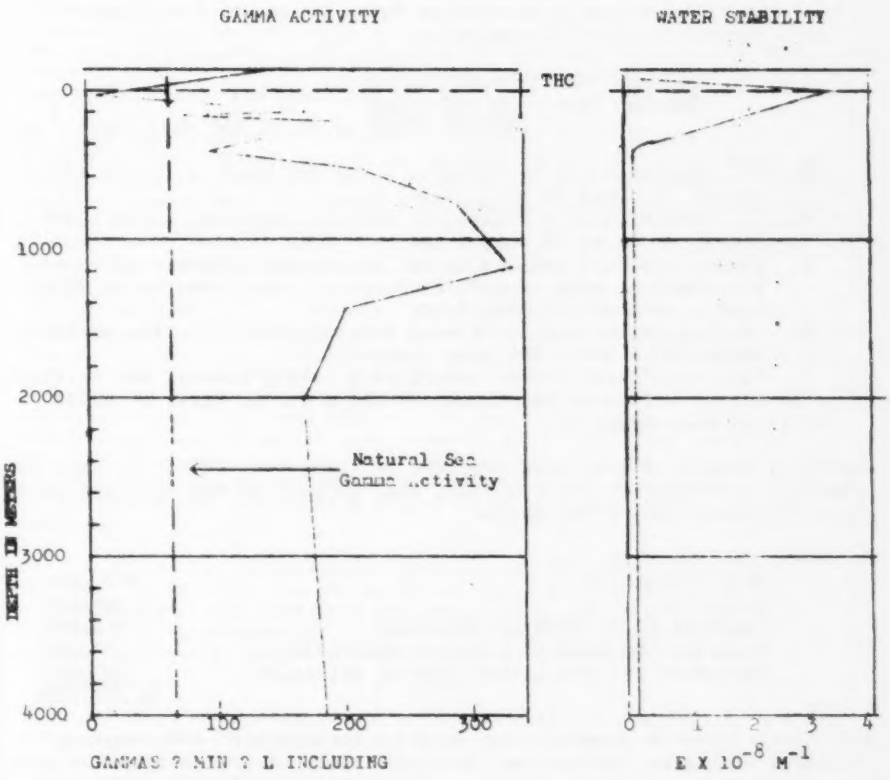
The left-hand curve in Figure 1 shows the vertical distribution of the average values of gamma activities measured in 1956 at ten (10) stations in the Marshall Islands. The accuracy of measurements is not great, but these data, nevertheless, appear to indicate that there existed in 1956 (two years after the previous weapons test) a body of water contaminated with fission products in concentrations of at least one order of magnitude above the natural gamma ray background of the sea (which is about 70 cpm per liter). A maximum value appears between the 800-1000 meter depth. It can be estimated that the activity in this deep pool could average as much as 1 megacurie per 4000 square miles of area. This activity should decay very slowly; and this and similar deep pools should be easy to locate and follow for years. Measurements of such a pool of radioactivity can be conducted by a small group with a relatively small budget. On a larger scale and with instruments of higher sensitivity fallout could be studied over much of the northern hemisphere.

Deliberate introduction of a sufficient amount of radioactive material in a line along the eastern margin of a deep western boundary current should allow measurement of the lateral spread eastward of the radioactivity, and thus give a direct measure of the mixing in the neighborhood of the current. Perhaps this also would allow an estimate of vertical mixing in the deep water.

International Collaboration

The world-wide character of the deep water problems means that international collaboration will be most helpful in attacking them. For example, studies of the deep western boundary current in the northwest Pacific will best be carried out in collaboration with the Japanese, and in the southwest Pacific, Australian and New Zealand ships could be used.

Because of the very high cost of high seas research, international collaboration will also be desirable equitably to distribute the necessary support.



AVERAGES OF TEN OCEANIC STATIONS NEAR NORTHERN MARSHALL ISLANDS IN 1956, ABOUT TWO YEARS FOLLOWING WEAPONS TEST.

Fig. 1

Estimate of financial support required

A. Estimate of ship operations

1. Direct measurements of the western boundary currents - 4 ships at 200 days each, or about 800 ship days.
2. Detailed east-west profiles - oceanographic stations at 100-mile intervals on 10 sections in the Pacific (about 60,000 miles) and 5 sections in the Indian Ocean (about 30,000 miles), or a total of about 1000 stations.

Station time	6,000 hours
Running time	10,000 hours
	16,000 hours or about 700 ship days

3. C^{14} samples in high latitudes - for 100 samples, about 600 hours, or about 30 ship days.
4. C^{14} samples in low latitudes - for 200 samples, about 1,200 hours, or about 60 ship days.
5. Fission product samples in and below mixed layer - if these are taken at each of 1000 hydrographic stations, about 2000 hours, or about 90 ship days.
6. Studies of the spread of deep radioactivity from the northern Marshalls - about 200 ship days.
7. Introduced radioactive materials to study lateral and vertical mixing - for one experiment, 5 ships for 30 days, or about 150 ship days.

The total number of ship days required is thus about 2000. If this is considered a five-year program, ship time amounts to 400 days per year, or the fulltime use of two ships.

B. Estimate of annual cost

Ship operations	$400,000
Salaries	600,000
Indirect Costs (40% of salaries)	240,000
Supplies and expense (10% of salaries)	60,000
Equipment and Facilities (15% of salaries)	100,000
	$1,400,000

Many other types of observations, such as measurement of the upward diffusion of ionium, radium and other naturally occurring radionuclides from the bottom; studies of ionium, thorium and lead ratios in the deep water; measurement of heat flow through the bottom; studies from anchored buoys; and studies of the near-surface and intermediate circulation, should be made simultaneously with the above more specific investigations. Moreover, as the results from these specific studies are analyzed, new types of observations will suggest themselves. The above recommended program thus represents only a part of what should be done, but it can be thought of as the major part of a five-year program.

Sedimentation Processes

Two significant concepts are involved in the bottom deposit accumulation of materials introduced into the ocean. The first involves the mechanisms for removal, both inorganic and biochemical. The second is concerned with the average time an element spends in seawater before incorporation into the sediments.

The inorganic transfer of chemical elements from the seawater to the sediments occurs principally at the sediment-water interface. Only the processes involving the minor and trace metals have been treated extensively and these will be discussed for illustrative purposes. In deep sea deep sea sites three minerals are responsible for the removal of heavy metals: the ferro-manganese oxide minerals; the zeolite phillipsite and the microcrystalline skeletal apatite from marine vertebrates. Each of these three mineral groups concentrate a typical suite of elements by different processes. The ferromanganese oxide minerals accumulate the transition, actinide and lanthanide metals by incorporation into one of the disordered layers of their structure. The phillipsite concentrates preferentially metallic ions with a high charge and a large radius by ion exchange mechanisms. Finally, the microcrystalline apatite-protein aggregates take up elements in two ways. The proteinaceous phases extract metals such as zinc, copper, lead and silver, probably by chelation by organic functional groups; the phosphate phase is enriched in the actinides, lanthanides and heavy alkaline earths by either exchange or sorption reactions on their very large internal surfaces.

The formation of such authigenic minerals as the marine clays, the ferro-manganese minerals, the zeolites, etc., as well as the alteration of detrital minerals, involves the uptake of a host of elements from seawater. Yet, practically no work has been done on anionic interactions or upon the minor or trace elemental composition of the clay minerals.

The biological components in the sediments arise principally from reactions in the overlying water column and can be classified into two general categories: the skeletal materials, including silicon dioxide, calcium carbonate and calcium phosphate and the organic phases. The impurities in these phases, i.e. the accommodated metallic and non-metallic elements excluding carbon, oxygen, hydrogen, nitrogen and sulphur are poorly known both quantitatively and qualitatively.

The average time an element spends in seawater before removal by biological and/or inorganic processes has been calculated in two ways, both of which assume a steady state system in the oceans. The first involves the amounts of elements brought in per unit time by the rivers and the second considers the amounts of elements precipitated to the ocean bottom per unit time. Both computations give results that are remarkably similar. A wide spectrum of elemental residence times exists; e.g. sodium apparently lives in the ocean for around a billion years before going to the bottom while aluminum spends closer to a hundred years in the marine hydrosphere.

A series of important initial experiments are listed below. Such work will lead to other and more definitive investigations.

Residence times of elements in the oceans

The residence times cited in the previous paragraphs are based upon a knowledge of the concentration of elements in seawater, concentrations in pelagic sediments and the rates of accumulation of sediments. Initial experiments should be aimed at measurement of the concentration of the elements of the fission product spectrum in all major oceanic basins in both deep and surface waters. The ship time involved would be of the order 12 hours per station in about 50 stations or about twenty-five ship days.

Certain sedimentary areas are poorly defined with respect to build-up in bottom deposits. Cores from such areas, principally the western Pacific, Indian Ocean and South Atlantic would be especially desirable. The ship time involved would be of the order of 4 hours per station about 60 stations or 10 ship days.

Finally, it would be useful to make detailed studies of the depth profiles of elements in seawater whose residence times are small, i.e., aluminum, titanium, thorium, etc. with values under ten thousand years. Such analyses may prove useful in delineating both deep and surface water masses. The ship time could be included in the trace element analyses cited above.

Inorganic transfer of chemical species from seawater to the sediments

Probably the most difficult and also the most exciting work would involve the anion-exchange characteristics of authigenic minerals, including the clays. It is difficult to outline any specific attacks that might be made; however, present techniques in soil sciences would at first be utilized in such investigations.

The relative abilities of each of the principal components of sediments to concentrate specific elements and the spatial distribution of such minerals over the ocean floor is of major importance. Sediment cores would be used both in these studies and in the rate of build-up studies mentioned above.

Budget estimates

This whole investigation might best be carried out in one or two laboratories possessing the necessary equipment (infrared spectral analyzers, x-ray diffraction and fluorescence, gamma, beta and alpha spectrometers, magnetic and electrostatic separators, etc., coupled with the normal laboratory supplies and equipment) rather than piecemeal in various small laboratories. The well-equipped laboratory represents an investment of at least $200,000 and requires a maintenance capital of 5% or

$10,000 per annum. Further, a concentration of scientists thinking about these problems in one place appears desirable. It appears that roughly 5 senior scientists with double that number of technicians on a budget of $100,000 per year would be necessary.

A. Residence times of elements in the oceans	
Ship time (35 days)	$ 35,000
Salaries	60,000
Indirect costs (40% of salaries)	24,000
Supplies and expenses (10% of salaries)	6,000
Equipment and facilities (15% of salaries)	9,000
	$134,000
B. Inorganic transfer	
Installation of laboratory	$200,000
Salaries	100,000
Indirect costs (40% of salaries)	40,000
Supplies and expenses (10% of salaries)	10,000
	$350,000

Note: After the first year, equipment and facilities would amount to $15,000 per year, so that the annual total for the second and following years of the program is $165,000.

Effects of the Biosphere on the Distribution and Circulation of Radioisotopes in the Sea

The distribution of radioactive elements introduced into the sea is profoundly influenced by the organisms living therein, since these organisms take up the radioisotopes along with the stable isotopes of many elements for use in their metabolic processes. Furthermore, many organisms exhibit significant motion, both horizontal and vertical, relative to their environment. Thus the net effect of the organisms is both to concentrate certain radioactive elements, and to transport them away from the region of introduction.

Therefore, it is clear that any attempt to predict the fate of radioactive material in the sea cannot succeed unless the role of marine organisms is understood. The importance of this knowledge is further underscored by the fact that the most serious potential hazards to human beings from the introduction of radioactive products into the marine environment may arise through the uptake of radioisotopes by organisms used for human food.

Objectives and scope of program

The biological transport of radioisotopes in the sea depends upon the size, specific characteristics and distributions of the populations of organisms involved, upon the accumulation of various elements by various species within the population and upon the movements of organisms which

are independent of water mixing and currents. The physiological state of the organisms in the population will modify the processes - for example, an actively growing population will accumulate elements more actively than a stable or a senescent population, and a dying population of zooplankton will settle more rapidly than a healthy living population.

The distribution of radioisotopes which are combined with plants and animals will be modified by the gravitational effects on the organisms themselves and on their faecal material, and by active migrations of the animals in both vertical and horizontal directions. Diurnal migrations of the pelagic populations will transport radioisotopes from levels of high to those of low concentrations. The elements most effectively transported by such repeated migrations will be those which are readily and rapidly exchanged with the water. In contrast the elements which will be most readily transported by sedimentation will be those which are bound firmly in the organic or skeletal structure. To evaluate these processes it will, therefore, be essential to have careful rate studies of the accumulation and exchange, as well as determinations of the steady state accumulations at various environmental concentrations.

Much can be learned from specific investigations of the rate of accumulation and loss of radionuclides through laboratory studies employing radioisotopes as tracers. This work can only be carried out, however, with certain species since many of the pelagic species cannot yet be maintained in the laboratory. Careful elemental analyses of various species obtained in the open sea are also necessary. For the most part, earlier studies of the elemental composition of marine organisms were incomplete and carried out with methods considered today as unreliable. Continuing research on the elemental composition of marine life, using the most modern research tools of chemistry and radiochemistry, is required to ascertain the accumulation levels of radioactive contaminants.

Particularly pertinent in the studies of availability and rate of uptake of radionuclides are questions as to the foods and feeding behavior of marine animals. We have at present only limited information on the foods of marine fishes and a few invertebrates. We have almost no information on the quantities of food involved.

In the vicinity of radioactive disposal areas, detailed ecological studies of the important populations of organisms at all trophic levels, and the exchange of radioactive materials between trophic levels, are necessary. These must extend for a sufficient length of time that seasonal changes are well established.

It has been calculated (Ketchum & Bowen, 1958 - paper submitted for presentation at Geneva Conference on Peaceful Uses of Atomic Energy) that vertical migrations of plankton could transport isotopes from a deep contaminated area to the surface more rapidly than has been proposed for the rate of transport by physical processes. The importance of the biological transport increases as the size of the migrating population increases and as the concentration factor for the isotopes by the

organisms increases. A full evaluation of the problem, however, requires better knowledge of the distribution of organisms, of the extent of their vertical migrations, and of the affinities of different organisms for different isotopes.

Present knowledge

General information is available and studies are in progress concerning the size and distribution of zooplankton populations in various areas. Considerable work is in progress on determining the rate of production of phytoplankton populations in the sea, though there is still confusion concerning the significance of various methods of determining basic productivity. Although there has been considerable interest in the deep scattering layers, little is known as yet concerning the sizes of the populations undergoing the migrations, and there is even less agreement concerning the species composition of the migrating populations. The transfer of elements from one trophic level to another among marine species needs much more study. Experiments on the efficiency of ingestion and digestion of food by organisms in various trophic levels, the excretion of elements into the water and the proportion of material discharged as faeces will be needed to evaluate the effects of various trophic levels on the transport of isotopes.

Program of Research

A. Basic Productivity
   1. Evaluation of methods: comparison of methods under various ecological conditions, evaluation of the physiological state of populations (active growth, stability or senescence)
   2. Environmental studies: evaluation of limiting factors (light, transparency, nutrients, trace elements, etc.), and conditioning factors (temperature, salinity, pressure, etc.)
   3. Exploration: Comparison of seasonal productivity in different types of areas (estuaries, coastal waters, open ocean), comparison of different geographical areas.

B. Zooplankton
   1. Development of better methods for collection.
   2. Study of vertical distribution and migrations: species composition and population size, diurnal and seasonal changes, factors controlling vertical migration.
   3. Patchiness studies: reproducibility and significance of collections.
   4. Feeding experiments: evaluation of efficiency of trophic levels in natural environments.

C. Benthic Populations
   1. Size and species composition of populations in various habitats.
   2. Sources of food and feeding habits.
   3. Food chains leading to shellfish and edible fish.

D. Fish and Marine Mammals
   1. Distribution and horizontal migrations of important commercial species.
   2. Sources of food and feeding habits.
   3. Uptake of radioactive isotopes, and sites of deposition.

E. Elemental analyses of representative invertebrate and vertebrate organisms.

F. Ecological studies of representative disposal areas.

Note: Some of these problems could be studied by a single group and the solution would be applicable to populations everywhere. The studies of the geographical distribution of populations would, however, require support in various suitably equipped laboratories. The work at sea should be coordinated with the physical oceanographic studies of circulation and mixing.

Estimate of annual cost

A-D Basic Productivity, Zooplankton, Benthic Populations, Fish and Marine Mammals	
Ship time (200 days)	$200,000
Salaries (40 people at average $6000)	240,000
Indirect costs	96,000
Supplies and expenses	24,000
Equipment and facilities	40,000
	$600,000
E. Elemental Analyses	
Salaries (10 people at average $6000)	$ 60,000
Indirect costs	24,000
Supplies and expenses	6,000
Equipment and facilities	10,000
	$100,000
F. Ecological studies of disposal areas	
Ship time (60 days)	$ 60,000
Salaries (18 people at average $6000)	108,000
Indirect costs	44,000
Supplies and expenses	10,000
Equipment and facilities	16,000
	$238,000

Note: This program represents the biological part of the studies described in the section "Control and Monitoring of Waste Disposal" but these funds are in addition to the annual amounts stated there.

The Genetic Effects of Radiation Upon Marine Organisms

The genetic effects of atomic radiations on marine organisms have been largely neglected. In general, the more complex the organism, the larger is its susceptibility to radiation damage. However, embryonic forms are especially vulnerable to radiation, and in the event of the discharge of high level radioactivity in partially confined waters, the intensity of radiation may constitute a hazard.

Some information is available about the levels of radiation required to produce morphological damage or death in marine organisms, particularly in fish. But mutations may occur at much lower radiation levels. Obviously we should know what these levels are, and what the mutation rate is for organisms in all trophic levels.

Both phyto- and zooplankton can become irradiated by adsorbed radionuclides; that is, the nuclides need not be absorbed. The adsorptive properties of some fission products vary with salinity and pH. Furthermore, some radionuclides are concentrated by marine organisms manyfold, and the total radiation dose may be far in excess of what would be calculated by measuring the radiation/unit volume of water. It is conceivable that the radiation dose to marine organisms in an estuary after a nuclear power accident from a ship would be of the order of 100 rads/year (based on calculations by Revelle and Schaefer: Oceanic research needed for safe disposal of radioactive wastes at sea).

Possible genetic effects should be studied even at the low radiation levels that will result under steady state conditions in the oceans from continuing disposal of radioactive wastes. These effects should be studied at all trophic levels because the population of an important link in the food chain may be greatly changed thus ultimately affecting organisms at other trophic levels which may have economic significance.

It is suggested that these investigations be carried out by individual geneticists or small groups in universities or government laboratories.

At the beginning four such groups should be supported at a level of $25,000 a year each, or a total of $100,000 per year. This work could receive diversified support. In particular it would seem pertinent to interests of the AEC, the U.S. Fish and Wildlife Service, the National Institutes of Health, and the Committee on Growth

FIELD EXPERIMENTS UTILIZING RADIOISOTOPES

Introduction of fission products into small confined bodies of water

Several objectives could be accomplished by the introduction of relatively large quantities of fission products into a lagoon. With a single dose, a condition simulating a nuclear power disaster from a ship could be studied in great detail. For example, it would be possible to study mixing time, the rate of uptake of the individual isotopes by marine organisms, the localization of these isotopes within the organisms, the biological transfer of these isotopes by way of the food chains, biological exchange with the bottom, and also ecological effects.

This objective could be accomplished by the introduction of about 100 curies of mixed fission products into an acre of water six feet deep. This amount of radioactivity can be safely contained in something less that three gallons of liquid, and the logistics of handling it are not formidable.

This experiment would also be valuable in giving an approximate answer to the question of what might occur in the oceans in the event of a nuclear war. The levels of radioactivity of isotopes hazardous to man that are found in the edible parts of marine organisms could be obtained directly.

If a larger and deeper body of water were available which contained plankton exhibiting rhythmic vertical movement, it might be possible to assess the role of these organisms in the vertical transfer of fission products in the ocean. A large amount of radioactivity could be introduced at the bottom. The radioactivity present in the water and in the plankton at various depths as a function of time would indicate to what extent these organisms can exchange stable for radioactive atoms and thus contribute to the physical factors responsible for the vertical distribution of radioactivity. This physical mixing time would have to be small enough so that concentration gradients due to the plankton migration would be measurable.

The continual introduction of small quantities of fission products into a lagoon would simulate the steady state condition that will occur as fallout and reactor wastes reach the sea. A long term study of such a lagoon should be made primarily from an ecological standpoint. Here again the biological transfer of radioactivity could be studied, as well as the dynamics of population changes which may be related to long term radiation effects.

The knowledge we have about the localization of radioisotopes within marine organisms is based upon studies in the laboratory. These studies are very valuable, but they should be extended by studying a much wider variety of organisms, many of which cannot be kept in captivity.

The information available about the biological transfer of radioactivity by way of food chains is meagre, and depends for the most part on studies of the concentration reached by organisms from different trophic levels following exposure for limited periods to radioactivity.

A few experiments are in progress involving the labelling of primary producers which are then fed to their predators and so on up the food chain. These studies can indicate approximate rates of transfer and concentrations reached at the different trophic levels, but are limited by the fact that the food chains are artificial and do not represent the over-all conditions found in nature. The numbers obtained may differ from those that may be found in nature by orders of magnitude.

A single group could probably best undertake a study of this kind. This group should include taxonomists, ecologists, and radiochemists. Living facilities would have to be provided at the site, but perhaps the radiochemical analysis might be done in an urban area.

About 5 to 10 people would be adequate, on a budget of about 100,000 a year.

Field experiments with specific organisms as chemical concentrators

Niobium, one of the important long lived fission products, after some time following introduction to the marine environment, probably exists in chemical equilibrium with natural niobium with respect to ionic species. Radioactive niobium is easily assayed with simple gamma-ray spectrometric equipment.

On the basis of the work of Carlisle and Humberston (Nature, 181, 1002-3 1958) and others at the Marine Biological Laboratory in Plymouth, England, it appears that (1) certain tunicates concentrate niobium which is present in sea water in ionic form (2) certain tunicates concentrate ionic vanadium and (3) some concentrate neither vanadium nor niobium but none concentrate both.

One of the niobium concentrators is Molgula manhattensis, a creature which lives up and down the Atlantic coast. A similar niobium concentrator may be found on the Pacific coast.

A program to monitor these organisms in an area of radioactive disposal might be initiated. Information regarding the entry of niobium into surface waters is certainly of profound interest. If such work is begun now and carried out continuously, the successive stages of possible contamination of harbors might be determined. To be successful, the obvious scientific controls of sampling, age of organisms, seasons of the year, etc., must be imposed upon such experiments.

Field experiments using radioisotopes to study physical processes in the ocean

In Chapter 12 of NRC Publication No. 551 "The Effects of Atomic Radiation on Oceanography and Fisheries" entitled "The Tagging of Water Masses for the Study of Physical Processes in the Ocean", three particularly important large scale tests were outlined and suggestions were made as to how to best carry them out with the techniques and instruments

available in 1956. The three important regimes of the open sea appeared to be the wind-mixed surface layer, the very stable mid-depth layer in the thermocline, and the slightly stable bottom water.

During the past two years, several advances made in the marine sciences have increased the feasibility and desirability of these experiments. Among these advances are:

1. An increase in the number of scientists and oceanographers who have concerned themselves with radiological problems of the sea;
2. More precise navigation, using precision echo sounders, moored buoys, and electronic navigational devices, the latter being especially useful within 300 miles of a continental or island coast;
3. Deep Sea electrical cables have been used with considerable success down to 3000 meters and tests are underway down to 6000 meters. The ability to telemeter multiple information channels over a single wire is advancing very rapidly;
4. Development of fullspeed underway towing, down to 150 meters, of electrical measuring elements which can continually record on deck multiple electrical measurements along the towed string.
5. The sensitivity of the radiation measuring elements suitable for deep sea observation has improved 10 to 100 fold;
6. Many subsurface current measurements have been made with the Swallow float and the Volkman drogue - nearly all U. S. oceanographic laboratories are using or building these devices.
7. Development of techniques for handling quantities of radioactivity in multiples of 10^4 curies in other ways than by using a nuclear weapon as a source

Specific field tests

The transition from laboratory tests to open ocean tests is largely one of facing the problems involved with large quantities of radioactivity, less proven techniques, navigational uncertainties, the vagaries of the weather, and the complexity of the ocean. Perhaps the hardest decision is whether to use mixed fission products or a single isotope. The latter would be preferable from most points of view, but it might require more of a single isotope than would be available at a reasonable cost.

The three basic tests outlined in Chapter 12 of NRC No. 551 still appear to be the most promising. Appendix 1 gives a detailed discussion of the ways in which improved techniques might affect the results of these experiments.

Participation in Oceangoing Radiological Measurements

Radiological contamination at sea, waste disposal, and a better understanding of uptake by the food chain are problems of international importance. For their solution, the cooperative efforts of all interested scientists are needed. Because some countries may be more concerned

with the possibilities of radioactive waste disposal at sea than the United States it should not be difficult to enlist their efforts in joint experiments, perhaps in tests near their territorial waters.

Budget Estimate

Measurements at sea are so dependent upon the capabilities of seagoing instrumentation that our national program for developing specific instruments for ocean radiological measurements should be accelerated. An annual budget of $1,000,000 for this purpose would constitute an increase of about 25% and insure that instrumentation for ocean going radiological measurements would be adequate for the programs that need to be undertaken.

Budget for large open sea tests

4 ships at 100 days each at	$1,500	$600,000	
			$600,000
4 special winches and cables at	$25,000	100,000	
4 sets recording equipment at	$10,000	40,000	
10 sets probes at	$ 2,000	20,000	
Other		100,000	
			260,000
Scientific personnel (preparation-testing-analysis) 30 man years at	$10,000		300,000
Travel, etc.			30,000
Navigational aids (buoys, etc. off shore) (EPI - near shore)			100,000
20,000 curies at the dock with container			50,000
Engineering and barge to permit releasing at depth			200,000
Contingencies			460,000
Overall cost of a major off shore test			$2,000,000

The cost of such an experiment could vary widely, a limited experiment conducted close to a home port with 1000 curies or less might be done for $400,000, while a large, long running experiment conducted far afield might cost over $5,000,000.

The greatest good might be obtained by holding a series of field tests every other year. This would encourage long term planning and would attract more non-oceanographers. These tests would become larger and more complex as our ability and knowledge improved and as the urgency of such matters became more pressing.

SUMMARY OF BUDGET ESTIMATES

	annual cost
II. Estuarine and Coastal Studies	
Estuarine physical studies	1,400,000
Coastal physical studies	1,400,000
III. Research in the Open Ocean	1,400,000
IV. Sedimentation Processes	
Residence times	134,000
Inorganic transfer	350,000 (1)
V. Effects of the Biosphere	
General problems (-D)	600,000
Elemental analyses	100,000
Ecological studies of disposal areas	238,000
VI. Genetic Effects	100,000
VII. Biological Field Experiments	100,000
VIII. (Physical Oceanographic Field Experiments - 400,000	- 2,000,000
TOTAL (2)	$5,822,000 (3)

(1) $165,000 for succeeding years

(2) Excluding item VIII for which estimates are considered too uncertain.

(3) $5,657,000 for succeeding years excluding item VIII

Obviously much of the research contemplated in this report cannot be completed in a few years. However, a five-year program of the magnitude described would lead to a significant advance in our understanding of the processes affecting the distribution of radioactive materials in the sea. A much better estimate of the quantities of radioactive materials which could be safely introduced into the various types of marine environments would then be possible.

A total estimated cost of this five-year program is $30,000,000. It should be pointed out that there is a certain amount of overlap between the proposed program and existing investigations of oceanographic and fisheries research organizations in this country. Approximately a third of the five-year total, or about $10,000,000 represents work now underway, the remaining 20,000,000 representing essential new effort.

Oceanography 1960 to 1970--A Report of the
Committee on Oceanography of the
National Academy of Sciences
(February 1959)

CHAPTER 1

INTRODUCTION AND SUMMARY OF RECOMMENDATIONS
of the Committee on Oceanography
National Academy of Sciences-National Research Council

Harrison Brown, California Institute of Technology,
Pasadena, California

I. INTRODUCTION

Two-thirds of the earth's surface is covered by the waters of the seas. The waters themselves greatly affect our lives--they play a major role in governing our climate; they provide inexpensive transportation; from them we derive important quantities of nourishment; they have traditionally provided protection against military attack. Beneath the surface a myriad of wonders is concealed. There are trenches, the floors of which are as much as 7 miles below sea-level. Mountains which approach Mt. Everest in height rise up from the ocean floor. Sediments in the ocean deeps contain detailed records of earth history--and, associated with it, life history. The more than 300 million cubic miles of water contain huge assemblages of living matter of fantastic variety.

As our technological civilization increases in complexity, as human populations grow more and more rapidly, as problems of military defense become increasingly difficult, as man pushes forward with his relentless quest for greater understanding of himself, his origins and the universe in which he lives--as all of these changes take place, detailed knowledge and understanding of the oceans and their contents will assume ever greater importance.

Man's knowledge of the oceans is meager indeed when compared with their importance to him. Recognizing that neglect in this area of endeavor might well result in our

being placed in a precarious position from the scientific, technological and military points of view, the National Academy of Sciences-National Research Council decided in 1957 to form a Committee on Oceanography.* In May of that year President Detlev Bronk appointed Harrison Brown, Professor of Geochemistry at the California Institute of Technology, Chairman of the Committee. The Committee itself was formed during the following months and its first meeting was held in November 1957.

The members of the Committee are:

Harrison Brown, (Chairman), California Institute of Technology, Pasadena, California
Maurice Ewing, Lamont Geological Observatory, Columbia University, Palisades, New York
Columbus O'D. Iselin, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts
Fritz Koczy, Marine Laboratory of the University of Miami, Miami, Florida
Sumner Pike, Lubec, Maine, formerly Commissioner, U. S. Atomic Energy Commission
Colin Pittendrigh, Department of Biology, Princeton University, Princeton, New Jersey
Roger Revelle, Scripps Institution of Oceanography, La Jolla, California
Gordon Riley, Bingham Oceanographic Laboratory, Yale University, New Haven, Connecticut
Milner B. Schaefer, Inter-American Tropical Tuna Commission, La Jolla, California
Athelstan Spilhaus, Institute of Technology, University of Minnesota, Minneapolis, Minnesota
Richard Vetter, (Executive Secretary), formerly with the Geophysics Branch of the Office of Naval Research, Washington, D. C.

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*This is the third NAS/NRC Committee on Oceanography. The first was established in 1927 under the chairmanship of Dr. Frank R. Lillie. The second, chaired by Dr. Detlev Bronk, was established in 1949. The reader is referred to the following publications for additional background material on these two committees.

(1) Oceanography, Henry B. Bigelow, Boston and New York: Houghton Mifflin Co., 1931
(2) International Aspects of Oceanography, Thomas W. Vaughn et al., Washington, D.C.; National Academy of Sciences, 1937.
(3) Oceanography 1951, NAS-NRC Publ. 208, Washington, D.C. 1952, (out of print)

The work of the Committee was made possible by the sponsorship of several government agencies, all of which have interests in the oceans:

Atomic Energy Commission
Bureau of Commercial Fisheries
National Science Foundation
Office of Naval Research

The Committee was organized as a part of the Division of Earth Sciences of the National Academy of Sciences-National Research Council.

At the request of President Bronk, the Committee has made a survey of the present status of the marine sciences in the United States. It has attempted further to assess the major problems of operations, administration and funding in this area and to evaluate the probable needs for oceanographic knowledge in the years ahead. On the basis of its findings, the Committee has drawn up a series of recommendations which, if followed, can result in a strengthening of the marine sciences during the next ten years to a level which is consistent on the one hand with the assessed needs, and on the other with limitations such as the rates at which ships and laboratories can be built and new oceanographers can be trained. It should be stressed, however, that the Committee considers its recommendations minimal ones. Action on a scale appreciably less than that recommended will jeopardize the position of oceanography in the United States relative to the position of the science in other major nations, thereby accentuating serious military and political dangers, and placing the nation at a disadvantage in the future use of the resources of the sea.

The deliberations of the Committee were complicated by a number of factors: oceanography embraces many sciences--indeed "oceanography" encompasses the scientific study of all aspects of the oceans, their boundaries and their contents; research is undertaken in a variety of private and government laboratories; numerous government agencies have direct but differing interests in the oceans; funds are derived from many sources. In order to expedite the formulation of recommendations under these circumstances, several specialized panels*

*The Committee as a whole acted as a panel on Basic Research, on Education and Manpower, and on problems of Operations, Sponsorship and Funding.

were formed for the purpose of making specific studies:

Oceanographic Research Ships
New Devices for Exploring the Oceans
Ocean Resources
Radioactivity in the Oceans
International Cooperation in the Marine Sciences

The memberships of the panels are listed at the end of this Summary. The Committee on Oceanography is greatly indebted to the panel members, who gave extensively of their time to these studies, and without whose help the recommendations could not have been formulated.

The complete reports of the panels have been incorporated into the final report of the Committee. Chapter headings of the final report are listed inside the front cover of this Summary. Individual chapters will be made available separately through the National Academy of Sciences as soon as possible. In addition, a condensed version of the Committee's report shortly will be made available for widespread distribution. The reader is referred to individual chapters of the report for more detailed discussion of the background, facts and reasoning which have led to the recommendations summarized in Section III, General Recommendations.

II. THE IMPORTANCE OF THE PROBLEM

The Committee has found that relative to other areas of scientific endeavor, progress in the marine sciences in the United States has been slow. There has been a substantial amount of excellent work, more often than not undertaken under extremely difficult and trying circumstances. But generally speaking progress has not been rapid when compared with the essential and exciting information yet to be obtained by probing the vast and dark, but penetrable, depths of water which cover so much of the earth's surface.

The seas present a challenge to man which in magnitude approaches that of space. At least we have been able to observe the moon, planets and stars directly with our telescopes. But the ocean depths, shrouded in darkness, have been obscured from our view. We know less about many regions of the oceans

today than we know about the lunar surface. Yet we have learned enough to know that major features of the ocean floor--35,000 foot deep trenches; 2,000 mile long fracture zones; flat-topped under sea mountains; broad ocean long ridges; abyssal plains as flat as a calm sea--are uniquely different from anything either on the surface of the moon or on the land surfaces of earth. How and when were these features formed and why are they so different? An answer to these questions is essential if we are to decipher the history of our planet and its sister planets. Part of the answer lies in the records of ancient earth history locked in deep sea sediments; part will come from an intensive study of the rocks under the ocean. These studies, combined with studies of the waters and the living creatures of the sea, will also tell us much about the origin and evolution of life on earth.

During the last few years, four great subsurface ocean currents--rivers in the depths of the sea one thousand times greater in flow than the Mississippi--have been discovered using newly developed current measuring techniques. We suspect that others exist and we need to know where the waters come from and where they go.

On the practical side the problems to be solved concerning the oceans are at least as urgent as those of space. How many fish are in the sea? No man knows, nor do we know what determines the numbers of fishes in different regions, the quantities of plant and animal material on which they feed, or what could be done to increase these numbers. We must learn these things if we are to help solve the increasingly acute problems of providing animal protein food for the growing numbers of underfed people in the world. Given more study man can economically harvest considerably more food from the seas than is now possible. Considering the position of the United States in the community of nations, it seems appropriate, even essential, that we lead the way in this respect.

About a third of the energy of sunlight is used to evaporate sea water. This evaporation and the subsequent condensation are the primary means by which solar energy is absorbed in the atmosphere. There is good reason to believe that changes in the location where interchange of matter and energy takes place between sea and air affect persistent weather patterns. We know that the average weather conditions we call climate can change over a few decades, and we suspect that changes in the storage of gases and heat in the oceans will

profoundly influence the process. Studies of the mechanisms of interchange between the air-sea boundaries of regions where intense interchange occurs and of the slow mixing between the ocean deeps and the surface which controls storage of heat and gases are essential for further understanding, hence for prediction and possibility of control.

From the point of view of military operations there is no comparison between the urgencies of the problems of the oceans and those of outer space. The submarine armed with long range missiles is probably the most potent weapon system threatening our security today. It seems clear that the pressures of establishing effective bases, and of protecting ourselves from attack, are relentlessly driving us into the oceans.

The problems involved in military operations in the sea are enormous. We will not be able to navigate under the oceans with adequate precision until our knowledge is greatly expanded. Nor will we be able to detect submerged submarines efficiently unless we learn far more about the ocean depths than we now know. We will not be in a position to negotiate an adequate international submarine control and monitoring system until we have the ability to make the oceans transparent so that we can track all submarines in the oceans, both our own and all others. To accomplish this, we must place greater national emphasis on research in the marine geophysical sciences, on surveys of the ocean background against which tracking must be accomplished, and on the development of effective devices to achieve such ocean-wide surveillance. The Committee's recommendations constitute an essential first step in these directions.

With these problems and prospects in mind, this Committee has attempted to assess the steps which should be taken in order that the United States might possess outstanding capabilities in the oceanographic field, and in order that we might obtain sufficient knowledge in time to avert a "crash" program--which would be wasteful in terms both of money and valuable technical manpower.

The cornerstone of our oceanographic endeavors is basic research. We need to understand waves and the interactions between the atmosphere and the oceans. We need to know more about ocean currents and upwellings. More intensive studies should be made of the properties of sea water and of processes

of sedimentation. We should systematically study the life forms in the oceans in three dimensions. We should study the sea floor with instruments and we should send men down to look at it in many localities.

In view of the complexities of these problems the Committee has recommended that the level of basic research in these fundamental areas be substantially increased during the next ten years. This will require increases both in manpower and in facilities. Of particular importance among the facilities are ships, which are to the oceanographer what cyclotrons or reactors are to the nuclear physicist. He simply cannot undertake adequate research without them.

Our oceanographic research ships are inadequate for the job which must be done. Most of the ships are old and outdated. Many are obsolete and should be replaced by ships of modern design which will be more efficient to operate and from which a greater variety of scientific observations can be made. In addition, the number should be increased.

The oceanographer also needs improved instruments if he is to penetrate the water barrier and learn in detail about conditions at great depths. Thus far oceanographers have not been able to take full advantage of recent technological developments and, accordingly, the Committee has recommended the establishment of a program of broad scope, aimed at developing and using new instruments and devices for exploring the sea. Using new deep-diving vehicles, for example, it is now possible for man to observe directly the ocean deeps. It seems highly likely that within the next ten years men will descend through the water nearly seven miles to the deepest point on earth.

An integral aspect of a program for learning about the oceans involves our surveying them more or less routinely. The topography of the ocean floor should be mapped in detail. We should arrive at a complete picture of gravitational and magnetic forces and of ocean currents in three dimensions. Sufficient biological information should be gathered so that we can prepare accurate maps of the distribution of life in the sea.

All of these studies, together with others like them, will have bearing upon the more immediate practical problems which confront us in the military area and in the area of ocean resource development. In addition to this, however, it is clear that the applied research and development programs in these areas should be expanded.

In the Committee's attempts to give quantitative indications of the relative amount of effort which it believes should be placed upon various aspects of the proposed program by individual government agencies, suggested budgets have been compiled for a ten-year period. These suggested budgets, in the Committee's opinion, present a reasonable representation of the magnitude and kind of effort and the degree of interagency cooperation which will be required if the recommended goals are to be achieved. In addition, a budget permits a direct comparison of efforts in this field relative to the efforts in other fields of scientific and technological endeavor.

III. GENERAL RECOMMENDATIONS

The key to the growth of oceanography in the United States lies in basic research - research which is done for its own sake without thought of specific practical applications. The very nature of basic research is such that the problems which will be attacked and the results which will be obtained cannot be predicted. The very nature of applied research is such that its success depends upon the size of the reservoir of fundamental knowledge upon which it must draw. The rate of progress in the applied marine sciences will be determined in the long run by the rate of progress in the basic marine sciences.

The Committee has concluded that both the quantity and quality of basic research in the marine sciences can and should be increased substantially during the years ahead. Specifically the Committee recommends:

1. The United States Government should expand its support of the marine sciences at a rate which will result in at least a doubling of basic research activity during the next ten years.*

It should be emphasized that doubling the basic research activity will require more than doubling the total expenditures.

A large part of the deliberations of the Committee were devoted to discussions of the conditions under which basic research can flourish. First and foremost, progress depends upon the interests, experience and creative imaginations of individual scientists. But the individual scientist does not work in a vacuum. He must have instruments and facilities. He must live in an atmosphere which is conducive to creative activity. These necessities in turn give rise to problems involving marine research laboratories - problems of leadership, financial stability, flexibility, growth, academic associations and physical facilities.

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*In 1958 about 23 million dollars were spent by applied and basic oceanographic research. The basic research share of the total was not over 9 million. About 8 million of this, including the 1958 share of IGY expenditures, was Federal funds.

Not only for research but in order to exploit and use the oceans we need more detailed knowledge which can only be obtained through systematic surveys in three dimensions. These surveys should include such features as depth, salinity, temperature, current velocity, wave motion, magnetism and biological activity. It is essential that these surveys be conducted on an ocean-wide ocean-deep basis as quickly as possible. Our knowledge is now largely limited to waters 100 miles from shore and even here it is inadequate for present and future needs. Accordingly, the Committee recommends:

2. The increase in support of basic research should be accompanied during the next ten years by a new program of ocean-wide surveys. This will require a two-fold expansion of the present surveying effort.

We believe that, on a long-range basis, basic research coupled with systematic ocean surveys are of paramount importance in solving a number of urgent practical problems involving military defense, the development of ocean resources and possible future increases of radioactive contamination of the seas resulting from the rapid development of atomic energy. However, research and surveys must go hand in hand with a vigorous and imaginative applied research and development program. Accordingly, the Committee recommends:

3. The United States should expand considerably its support of the applied marine sciences, particularly in the areas of military defense, marine resources and marine radioactivity.

The implementation of these general recommendations requires action upon a number of broad fronts. More marine scientists must be educated. Additional ships and shore facilities must be built. New instruments and techniques must be developed. International cooperation in the marine sciences must be strengthened.

To achieve these aims in the next ten years will necessitate many agencies of the Federal Government working together both in planning and in providing the monies.* Taking into

*One method suggested for developing more effective interagency cooperation is through the proposed Federal Council for Science and Technology. This Council is described in "Strengthening American Science", a recent report of the President's Science Advisory Committee.

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account the relative degrees of interest and importance of oceanography to individual agencies, the Committee recommends:

4. The Navy and the National Science Foundation should each finance about 50% of the new basic research activity except ship construction. The Navy should finance 50% of the new research ship construction with the Maritime Administration and the National Science Foundation sharing the remainder. The Navy, through the Hydrographic Office, should finance 50% of the deep ocean surveys, while the Coast and Geodetic Survey should finance the balance. The Navy should sponsor completely all military research and development operations. The Bureau of Commercial Fisheries should finance the greater part of the recommended ocean resources program. The Atomic Energy Commission should finance the major part of the research dealing with the problems of radioactive contamination of the oceans. The National Science Foundation and the Office of Education should sponsor jointly the proposed program for increasing scientific and technical manpower in the marine sciences. Efforts aimed at fostering international cooperation in the marine sciences should be sponsored by the Department of State, the International Cooperation Administration and the National Science Foundation. Other agencies should take responsibility for certain aspects of the proposed program, particularly the Public Health Service, the Geological Survey and the Bureau of Mines.

Although the bulk of oceanographic research and survey work must of necessity be financed by the Federal Government, the value of state and private funds cannot be overestimated. Such funds are especially helpful for supporting initial exploratory basic research and for starting new laboratories. Accordingly, the Committee recommends:

5. Private foundations and universities, industry and state governments should all take an active part in the recommended program of expansion.

IV. SPECIFIC RECOMMENDATIONS

Education and Manpower

1. The universities now providing graduate education for oceanographers should be encouraged to increase the numbers and quality of their output. Some institutions which now teach oceanographers in only certain branches of oceanography should add professors in other fields to their faculties. These measures will require financial support.

2. Institutions which undertake considerable research, but provide no regular formal teaching in oceanography, could contribute greatly to the education of oceanographers at the highest level by close formal affiliations with universities. Conversely, universities should recognize their responsibilities in the education of oceanographers. They should welcome this affiliation with marine laboratories and arrange for the interchange of faculties. This will require financial support.

3. It may be desirable to develop oceanographic education at new centers. However, a "critical mass" of faculty in the basic sciences is essential for successful teaching of oceanographers. Such new centers should, therefore, be developed at universities which possess strong faculties in the sciences.

4. In order to finance new faculty in oceanography at existing or new teaching centers, the United States Government should provide funds on long-term commitments. This Committee recommends that about $500,000 per year be appropriated for salaries and the equipment and indirect costs associated with such positions. This program could be operated through the Office of Education.

5. In order to attract competent graduate students to the long and somewhat arduous schooling required of well-qualified oceanographers, it will be necessary to provide substantial long-term fellowships. It is believed that 80 fellowships should be supported on a five-year basis and at an average stipend of $3500 to $4000 per student each year. This will produce 12-15 new Ph.Ds per year (allowing a reasonable attrition factor) at an annual cost of about $300,000. This would provide approximately one-third of the student support that will be needed in order to double the number of oceanographers at the Ph.D level during the next ten years.

It is desirable that fellowships permit students to attend more than one university. This can provide students with well-rounded educations in all branches of oceanography without each university having to provide a full curriculum. Such a program should be handled through the National Science Foundation.

6. Efforts should be made in research and survey programs to use larger numbers of assistants at the Bachelor and Master's level in order to utilize more efficiently the limited number of persons available at the doctoral level.

7. Oceanographers should undertake more active recruiting of prospective oceanographers among undergraduate students of physics, chemistry, biology, and geology.

New Ships for Research, Development and Surveying

1. A shipbuilding program should be started aimed at replacing, modernizing and enlarging the number of oceangoing ships now being used for research, surveying and development. Specifically in the period 1960-1970 the research, development and survey fleet should be increased from its present size of about 45 ships to 85 ships. Taking into account the replacement of ships which must be retired during the next decade, this means that 70 ships should be constructed at a total estimated cost of $213 million.

2. The size ranges recommended for new oceangoing ships are: about 500 tons, 1200 tons and 2,200 tons displacement.

3. The conversion of vessels, which were originally designed for other purposes, into research, development or survey vessels is to be discouraged. Such conversions are generally uneconomical.

4. The recommendations for the construction of ships for specific purposes (basic research, military research and development, oceanic surveys, resources and fisheries) are given in Table 1.

5. The recommended size distribution for new ships is given in Table 2.

6. The Navy should provide about 50% of the financing for the construction of new ships for basic research, all of the financing for new ships for military research and development, and 50% of the financing for new ships for oceanic surveys. The Coast and Geodetic Survey should provide 50% of the financing for the construction of new ships for oceanic surveys. The Bureau of Commercial Fisheries should finance the construction of all of the new ships for marine biological resources and fisheries studies. The National Science Foundation and the Maritime Administration should each provide about 25% of the financing for new ships for basic research. The numbers of ships in each size category which should be built by each of the sponsoring agencies are given in Table 3.

7. Detailed recommendations for the scheduling of ship construction by each of the sponsoring agencies are given in Table 4. Estimated capital costs by year and by agency are given in Table 5, based upon the assumption that a 500 ton ship will cost about $1.65 million, a 1200-1500 ton ship will cost about $3.80 million and a 2000 ton ship will cost about $5.00 million.

8. The Maritime Administration should be consulted in the designing of all ships paid for from public funds and used for marine studies.

9. Research ships operated by private institutions like those operated by the Navy, Coast Guard, and Coast and Geodetic Survey should be exempt from those existing legal requirements for living accommodations, safety and the licensing of crews, which are practical and sensible only on large (3,000 tons) merchant ships.

10. All non-combatant surface ships used for research, development or surveying should be operated by the laboratory or agency directly concerned and should have civilian crews.

11. In most cases the annual costs of operating vessels for basic research by non-government laboratories should be paid for separately from the other expenses of research, for example, through a long term facilities contract distinct from any research contracts.

12. The costs of ship operations paid by the Federal Government should be subdivided as follows: the Navy should pay for 50% of the operational costs of ships used for basic research, all of the operational costs of ships used in military research and development and 50% of the operational costs of ships used for oceanic surveys.

The Coast and Geodetic Survey should pay for 50% of the operational costs of ships used for surveys. The Bureau of Commercial Fisheries should pay for the operations of ships used for resources and fisheries studies. The National Science Foundation should pay for 50% of the operational costs of ships used for basic research.

13. Estimated costs of ship operations, both by function and by agency, are given in Tables 6 and 7.

TEN YEAR PLAN FOR INCREASING THE UNITED STATES FLEET OF OCEANOGRAPHIC SHIPS

Table 1

Function of Ships

	Research	Military R and D	Survey	Resources and Fisheries	Total
Present Fleet	11	9	18	7	45
To be replaced	5	9	9	7	30
Still operational in 1970	6	-	9	-	15
Additional new construction	11	11	11	7	40
Total construction	16	20	20	14	70
Total Fleet in 1970	22	20	29	14	85

Table 2

Recommended Size Distribution of New Ships

Size	Research	Military R and D	Survey	Resources and Fisheries	Total
500 tons	5	10	4	12	31
1200 - 1500 tons	9	6	11	2	28
Larger than 2000 tons	2	4	5	-	11
Total	16	20	20	14	70

Table 3

Recommended Sponsors of New Ships

	500 tons	1200 - 1500 tons	Larger than 2000 tons	Total
Navy	12	18	8	38
Coast and Geodetic Survey	2	6	2	10
Bureau of Commercial Fisheries	12	2	-	14
National Science Foundation	3	-	1	4
Maritime Administration	2	2	-	4
Total	31	28	11	70

Table 4

RECOMMENDED SCHEDULING OF NEW SHIPS

(year denotes time ship is put into service)

	Navy			C and G S			B of C F			N S F			M A			Total		
Year	500	1200-1500	2000	500	1200-1500	2000	500	1200-1500	2000	500	1200-1500	2000	500	1200-1500	2000	500	1200-1500	2000
1960	-	2	-	-	-	-	-	-	-	1	-	-	1	-	-	2	2	-
1961	3	3	-	1	1	-	2	-	-	-	-	-	-	1	-	6	5	-
1962	3	3	1	-	-	1	2	1	-	1	-	-	-	1	-	6	5	2
1963	2	2	2	-	2	-	2	1	-	-	-	1	1	-	-	5	5	3
1964	2	2	2	1	1	-	2	-	-	1	-	-	-	-	-	6	3	2
1965	1	2	2	-	-	1	2	-	-	-	-	-	-	-	-	3	2	3
1966	1	2	1	-	1	-	2	-	-	-	-	-	-	-	-	3	3	1
1967	-	2	-	-	1	-	-	-	-	-	-	-	-	-	-	-	3	-
1968	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1969	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	12	18	8	2	6	2	12	2	0	3	0	1	2	2	0	31	28	11
		38			10			14			4			4			70	

Table 5

Estimated Capital Costs for New Oceanographic Ships by Agencies

(Millions of 1958 Dollars)*

	Navy	C and G S	B of C F	N S F	M A	Total
1960	23.95	5.45	3.30	1.65	5.45	39.80
1961	21.35	5.00	7.10	1.65	3.80	38.90
1962	20.90	7.60	7.10	5.00	1.65	42.25
1963	20.90	5.45	3.30	1.65	--	31.30
1964	19.25	5.00	3.30	--	--	27.55
1965	14.25	3.80	3.30	--	--	21.35
1966	7.60	3.80	--	--	--	11.40
1967	--	--	--	--	--	--
1968	--	--	--	--	--	--
1969	--	--	--	--	--	--
Total	128.20	36.10	27.40	9.95	10.90	212.55

*Budget allocations have been assigned to the year immediately preceding that in which the ship is to be put into service.

Table 6

Estimated Ship Operations Costs above Present Level
by Function

(Millions of 1958 Dollars)

Year	Research	Survey	Resources and Fisheries	Total*
1960	--	--	--	--
1961	0.60	0.65	0.30	1.55
1962	1.20	1.30	0.55	3.05
1963	1.80	2.00	0.85	4.65
1964	2.35	2.60	1.15	6.10
1965	2.95	3.30	1.40	7.65
1966	3.55	3.90	1.70	9.15
1967	4.15	4.60	1.70	10.45
1968	4.15	4.60	1.70	10.45
1969	4.15	4.60	1.70	10.45
Total	24.90	27.55	11.05	63.50

Table 7

Estimated Ship Operations Costs above Present Level
by Agency

(Millions of 1958 Dollars)

Year	Navy*	C and G S	B of C F	N S F	Total*
1960	--	--	--	--	--
1961	0.62	0.33	0.30	0.30	1.55
1962	1.25	0.65	0.55	0.60	3.05
1963	1.90	1.00	0.85	0.90	4.65
1964	2.47	1.30	1.15	1.18	6.10
1965	3.13	1.65	1.40	1.47	7.65
1966	3.72	1.95	1.70	1.78	9.15
1967	4.38	2.30	1.70	2.07	10.45
1968	4.38	2.30	1.70	2.07	10.45
1969	4.38	2.30	1.70	2.07	10.45
Total	26.23	13.78	11.05	12.44	63.50

*Excluding Military Research and Development Ship Operations

Shore Facilities for Basic Research

In order to derive the maximum knowledge from observations and collections made at sea, it is estimated that 60 technical persons must be available for the average ship involved in high seas research activity. Most of these persons are involved in landbased activities which require laboratories and associated facilities.

1. It is recommended that for every additional oceangoing research ship put into operation, an average investment of $1.5 million be made for essential shore facilities. These costs should be divided between the Navy and the National Science Foundation.

2. It is estimated that the costs of research other than ship operations will average about $1.2 million per ship per year. The Committee recommends that Federal funds for this purpose be divided between the Navy and the National Science Foundation.

The costs to each agency, by year, are given in Table 8. Capital allocations are assigned to the year preceding the placing of a new research ship into operation. Although Table 8 shows no increase in the operating costs of shore based facilities for basic research until 1961 when the first new ships are completed, we expect that plans now being made by various Federal agencies (mainly the National Science Foundation and the Navy) involving budgets for basic oceanographic research will be able to maintain the 1958 level of activity and allow for some buildup of staffs. Such plans should be strongly supported by the agencies, the Bureau of the Budget and the Congress in order to avoid a serious relapse of our present capabilities.

Table 8

Capital and Operating Costs of Basic Research other than Ships

(over and above present level in millions of 1958 dollars)

	Navy		National Science Foundation	
Year	Capital	Operating	Capital	Operating
1960	0.75	--	0.75	--
1961	0.75	0.60	0.75	0.60
1962	0.75	1.20	0.75	1.20
1963	1.50	1.80	1.50	1.80
1964	2.25	3.00	2.25	3.00
1965	1.50	4.80	1.50	4.80
1966	0.75	6.00	0.75	6.00
1967	--	6.60	--	6.60
1968	--	6.60	--	6.60
1969	--	6.60	--	6.60
Total	8.25	37.20	8.25	37.20

Ocean-Wide Surveys

The capital and operating costs for ships involved in surveys of the world ocean have been given in a previous section. However, it is estimated that substantial shore facilities are required for the purpose of evaluating the data collected at sea. It is estimated that capital costs for shore facilities for each new survey ship will average about $0.75 million. It is further estimated that operating costs for shore facilities will amount to about $0.75 million per survey ship per year.

1. The Committee recommends that for every new survey ship put into operation an investment of about $0.75 million be made for essential shore facilities.

2. It is recommended that an average of $0.75 million be allocated each year for the operation of shore facilities for each new survey ship placed in operation.

These costs should be divided between the Navy and the Coast and Geodetic Survey. The costs to each agency, by year, are given in Table 9. Capital allocations are assigned to the year preceding the placing of a new survey ship into operation.

3. Consideration should be given to conducting some aspects of the survey program through contracts with commercial organizations and private institutions.

Table 9

Capital and Operating Costs for Shore Facilities for Survey Work

(over and above present level in millions of 1958 dollars)

	Navy		Coast and Geodetic Survey	
Year	Capital	Operating	Capital	Operating
1960	0.38	--	0.38	--
1961	0.38	0.38	0.38	0.38
1962	0.75	0.75	0.75	0.75
1963	0.75	1.50	0.75	1.50
1964	0.75	2.25	0.75	2.25
1965	0.75	3.00	0.75	3.00
1966	0.38	3.75	0.38	3.75
1967	--	4.13	--	4.13
1968	--	4.13	--	4.13
1969	--	4.13	--	4.13
Total	4.14	24.02	4.14	24.02

Engineering Needs for Ocean Exploration

1. A vigorous program should be conducted for the development of manned submersibles that can operate down to and on the bottom of most of the ocean:

a) An improved bathyscaph using the best materials and techniques available should be designed and built immediately.

b) Following up the recent commendable ONR action in bringing the bathyscaph TRIESTE to the United States, it is recommended that funds be made available for a mother ship* together with auxiliary equipment in order to make maximum use of this deep submersible.

c) A continuous design and development program should be initiated aimed at building deep and mid-depth manned vehicles as the need arises and as the state of the art progresses.

2. The need for open-ocean manned research platforms which are stable, and which can remain in place so that time studies can be made, seems essential and the design for such a buoy should be started.

3. A major program should be supported aimed at developing and using anchored and drifting buoys for obtaining space and time coverage of ocean characteristics.

4. It seems likely that aircraft can be used effectively for some research and surveys on the open ocean, particularly for studies involving the joint problems of oceanography and meteorology. Nearly all laboratories will need single engine planes; several will need twin engined amphibious planes; some will need four engined commercial-type aircraft.

5. Surface icebreakers are of limited value to Arctic oceanographic research compared to properly equipped submarines. Efforts should be made to develop a submarine capable of breaking into and out of the ice.

6. Instruments should be developed for survey purposes which are more accurate, effective and trouble-free than those

*This is listed in the section on New Ships.

now in use. The techniques needed to use them more effectively should be developed. Specialized devices such as Loran C, inertial navigation equipment, gravity meters and stable platforms should be made available for research as well as surveys as soon as possible.

7. A major program aimed at developing new high-seas engineering techniques should be started. Our abilities to handle heavy equipment and to conduct such operations as drilling and bottom sampling at sea limit our operations at present. Many of these difficulties would be appreciably lessened given proper effort. We have not included the very important problem of drilling to the Mohorovicic Discontinuity in our budget because another Academy group is studying this problem.

8. Machine aids to computation and data storage have much to offer and should be budgeted.

9. High pressure facilities to permit controlled physical and biological experiments in the laboratory are needed.

10. Efforts should be made to secure the active participation of private industry in the development and manufacture of new devices and instruments for oceanographic research and surveying.

11. The unpredictable aspects of new devices makes difficult the formulation of an exact budget over a ten year time-scale. The Committee recommends that $48 million be allocated during the next five years. It further recommends that a minimum of $10.5 million be allocated each year thereafter. The cost of this program should be divided between the Bureaus of the Navy and the National Science Foundation.

Budget breakdowns are given in Tables 10 and 11.

Table 10

Estimated Annual Budget for Engineering Needs for Ocean Exploration

(millions of 1958 dollars)

	1960	1961	1962	1963	1964
Deep Manned Vehicles	2.0	2.0	3.0	4.0	4.0
Large Manned Buoys	0.3	2.0	1.3	0.2	0.2
Unmanned Buoys	0.8	0.8	0.9	1.0	1.0
Aircraft	0.6	1.3	1.0	2.0	1.2
Other Specialized Vehicles	2.0	1.0	1.0	1.0	1.0
Development of New Instruments	0.6	1.2	1.2	1.5	1.8
Other	1.1	1.2	1.2	1.2	1.3
Total	7.4	9.5	9.6	10.9	10.5

Table 11

Estimated Annual Budgets for Engineering Needs for Ocean Exploration by Agency

(millions of 1958 dollars)

Year	Navy Bureaus	National Science Foundation
1960	3.70	3.70
1961	4.75	4.75
1962	4.80	4.80
1963	5.45	5.45
1964	5.25	5.25
1965	5.25	5.25
1966	5.25	5.25
1967	5.25	5.25
1968	5.25	5.25
1969	5.25	5.25
Total	50.20	50.20

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Radioactivity in the Oceans

The widespread use of nuclear energy for peaceful or military purposes necessitates studies to determine the effects of radioactive contamination upon the oceans and the life therein. The Committee on Effects of Atomic Radiation on Oceanography and Fisheries in its report to the National Academy of Sciences made certain general recommendations concerning national policy in this area. Both the Committee on Oceanography and the Committee on Effects of Atomic Radiation on Oceanography and Fisheries believe that more specific and detailed recommendations can now be made.

1. A single agency should be given the overall responsibility and authority for regulating the introduction of radioactive materials in the oceans. Monitoring of disposal sites should be done by some agency other than the regulating agency. It is recommended that either the Coast and Geodetic Survey or the Public Health Service be made responsible for engineering studies in and near disposal areas, for routine monitoring of disposal areas and their surroundings and for a continuing assessment of the effects on the environments of added radioactive materials.

2. Vigorous programs should be started for the purpose of determining the circulation and mixing processes which control the dispersion of introduced contaminants in coastal and estuarine environments and in the open ocean. These studies represent the major part of the proposed budget in this area.

3. A program should be pursued aimed at determining the inorganic transfer of radioactive elements from seawater to the sediments.

4. Studies should be made of the effects of living organisms on the distribution of radioactive elements introduced into the sea.

5. The genetic effects of radiation upon marine organisms should be studied.

6. A variety of biological field experiments should be conducted utilizing radioisotopes.

7. The proposed budgets for the programs are given in Tables 12 and 13. The greater part of the program should be financed by the Atomic Energy Commission.

Table 12

Radioactivity in the Oceans
Summary of Budget Estimates

(annual cost in 1958 dollars)

	Without Ship Time	Ship Time	Total
Control and Monitoring	$ 370,000	--	$ 370,000
Estuarine and Coastal Studies	1,920,000	$ 880,000	2,800,000
Research in Open Ocean	1,000,000	400,000	1,400,000
Sedimentation Processes	449,000[1]	35,000	484,000[2]
Effects of the Biosphere	678,000	260,000	938,000
Genetic Effects	100,000	--	100,000
Biological Field Experiments	100,000	--	100,000
TOTAL First Year	$4,617,000	$1,575,000	$6,192,000
TOTAL Subsequent Years	4,432,000	1,575,000	6,007,000
About 1/3 is now underway.			
Net cost of new program first year:	$3,078,000	$1,050,000	$4,128,000
subsequent years:	2,954,000	1,050,000	4,004,000

If two large open sea tests are conducted, one in 1962 and one in 1966, the additional costs in those years will be:

	$1,400,000	$ 600,000	$2,000,000
TOTAL in those years	$4,354,000	$1,650,000	$6,004,000

1) $264,000 after first year

2) $299,000 after first year

Table 13

Radioactivity in the Oceans
Summary of Budget Estimates for New Research

(millions of 1958 dollars)

Year	Cost Without Ship Time	Ship Time	Total
1960	3.08	1.05[1)]	4.13
1961	2.95	1.05[1)]	4.00
1962	4.35	1.65	6.00
1963	2.95	1.05	4.00
1964	2.95	1.05	4.00
1965	2.95	1.05	4.00
1966	4.35	1.65	6.00
1967	2.95	1.05	4.00
1968	2.95	1.05	4.00
1969	2.95	1.05	4.00
Total	32.43	11.70	44.13

1) Primarily through use of ships now in service.

Ocean Resources

Lack of adequate understanding of the occurrence, behavior and potential harvest of fish and other marine organisms serves as a serious barrier to extensive economic development and utilization of marine biological resources. Existing knowledge is inadequate to evaluate the feasibility of creating a marine mineral industry.

1. The sea and its contents should be studied on a broad basis to enlarge our knowledge of its potential resources.

2. In order to elucidate the problem of population fluctuations of commercial fish stocks, which in large part is due to variable infant mortality, laboratory studies of the survival requirements of larval and juvenile stages of commercially important fish and shell fish are needed urgently.

3. There is an urgent need for facilities for studies of fish behavior in the laboratory under controlled conditions. This will require aquarium facilities of sizeable physical dimensions.

4. Greater attention should be given to studies of the genetics of fish and other marine organisms.

5. Investigations should be made of the feasibility of adding nutrients to the euphotic zone of the sea in order to increase the productivity of marine organisms.

6. A program to investigate the possibilities of transplanting useful organisms from one region of the sea to another should be conducted.

7. More research is needed on the nature of the aggregations of organisms in the sea.

8. Biological surveys in the seas should be intensified, and programs should be initiated aimed at utilizing new devices such as unmanned buoys and the mesoscaph..

9. A data center for all oceanographic research should be established for the storage, routine processing and "read-out" of such information as sea surface temperatures, currents and

meteorological data. This data center would not perform the functions of more specialized computing centers such as will be required for oceanographic forecasting.

10. There is a need for scientific, sociological and engineering studies directed toward the wider utilization of marine products in protein-deficient areas of the world.

11. There is a pressing need for studies of the economic and legal aspects of commercial fisheries, especially in comparison with other industries, in order to provide a basis for national policy decisions.

12. A scientific study of salt water fish pond culture should be started aimed at providing a basis for greatly increasing the efficiency and productivity of this industry and thereby increasing the protein food supplies in protein-deficient areas such as Southeast Asia.

13. Many aspects of the potential mineral resources on the deep sea floor should be investigated. Such work should be supported through the Bureau of Mines.

14. An expanded program of estuarine research is recommended in order that we can make most effective use of this habitat of important resident stocks of food fish and shellfish and the nursery areas for other stocks which are later harvested from the open ocean.

15. Many lines of marine research depend upon precise definition of species. The study of species is centered in research museums which generally have been supported very poorly. It is recommended that established museums having significant study collections be given financial support so that this kind of work can be carried forward.

16. It is recommended that a program on diseases and other toxic effects in the marine environment be established.

The proposed budgets for these recommendations are given in Tables 14, 15 and 16. The mineral resources investigation should be sponsored by the Bureau of Mines with the balance being supported by the Bureau of Commercial Fisheries through grants, contracts and in its own laboratories and with the assistance of other branches of the Department of the Interior. Programs involving international cooperation and technical assistance to other countries budgeted under this heading should be supported at least in part by the International Cooperation Administration and the State Department.

Table 14

Capital Costs for New Ocean Resources Studies[1)]

(millions of 1958 dollars)

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	Total
Laboratory Survival Studies	0.50	--	--	--	--	--	--	--	--	--	0.50
Fish Behavior Studies	--	2.10	--	1.90	--	--	--	--	--	--	4.00
Supplementary Data Collection	0.04	--	--	--	--	.04	--	--	.04	--	0.12
Unmanned Buoy Utilization	--	0.20	0.20	0.30	0.30	0.50	0.50	--	--	--	2.00
Mesoscaph Utilization	--	--	--	--	1.00	--	--	--	--	--	1.00
National Data Center	0.25	--	--	--	--	--	--	--	--	--	0.25
Disease and Related Studies	--	--	--	0.80	--	--	--	--	--	--	0.80
Total	0.79	2.30	0.20	3.00	1.30	0.54	0.50	0.00	0.04	0.00	8.67
Mineral Resources Investigation	0.10	--	--	--	--	--	--	--	--	--	0.10
Total											8.77

1) Does not include capital costs of ships, which will be found in the section on New Ships.

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Table 15

Operating Costs for New Resources Studies[1)]

(millions of 1958 dollars)

	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	Total
Laboratory Survival Studies	--	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	2.16
Fish Behavior Studies	--	--	0.48	0.48	0.95	0.95	0.95	0.95	0.95	0.95	6.66
Genetics of Marine Organisms	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	2.00
Nutrient Increase Studies	0.12	0.12	0.12	0.15	0.15	0.15	0.15	0.15	0.15	0.15	1.41
Organism Transportation Studies	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.50
Organism Distribution	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.50
Biological Surveys	1.80	1.80	1.80	1.80	1.80	3.60	3.60	3.60	3.60	3.60	27.00
Supplementary Data Collection	0.11	0.11	0.11	0.11	0.11	0.22	0.22	0.22	0.33	0.33	1.87
Unmanned Buoy Utilization	--	0.03	0.06	0.11	0.15	0.23	0.30	0.30	0.30	0.30	1.78
Mesoscaph Utilization	--	--	--	--	--	0.64	0.64	0.64	0.64	0.64	3.20
National Data Center	0.10	0.11	0.12	0.13	0.15	0.16	0.18	0.20	0.22	0.24	1.61
Marine Product Utilization	0.30	0.30	0.30	0.30	0.30	1.00	1.00	1.00	1.00	1.00	6.50
Economic and Legal Studies	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	2.00
Pond Fish Culture	0.10	0.10	0.10	0.10	0.30	0.30	0.30	0.30	0.30	0.30	2.20
Estuarine Studies	0.20	0.20	0.50	0.50	0.50	0.50	0.50	0.80	0.80	0.80	5.30
Taxonomic Development	0.55	0.55	0.55	0.55	0.55	1.00	1.00	1.00	1.00	1.00	7.75
Disease and Related Studies	--	--	--	0.20	0.20	0.20	0.50	0.50	0.50	0.50	2.60
Special Development Fund	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	1.00
Total for Bureau of Commercial Fisheries	3.88	4.16	4.98	5.27	6.00	9.79	10.18	10.50	10.63	10.65	76.04
Mineral Resource Investigation (Bureau of Mines)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	2.50
Total	4.13	4.41	5.23	5.52	8.25	10.04	10.43	10.75	10.88	10.90	78.54

1) Excluding Ship Operations.

Table 16

Capital and Operating Costs for New Resources Research[1)]

	Bureau of Commercial Fisheries		Bureau of Mines		
Year	Capital	Operating[2)]	Capital	Operating	Total
1960	0.79	3.88	0.10	0.25	5.02
1961	2.30	4.16		0.25	6.71
1962	0.20	4.98		0.25	5.43
1963	3.00	5.27		0.25	8.52
1964	1.30	6.00		0.25	7.55
1965	0.54	9.79		0.25	10.58
1966	0.50	10.18		0.25	10.93
1967	--	10.50		0.25	10.75
1968	0.04	10.63		0.25	10.92
1969	--	10.65		0.25	10.90
Total	8.67	76.04	0.10	2.50	87.31

1) Excluding ships and ship time.

2) Programs involving international cooperation and technical assistance to other countries budgeted under this heading should be supported at least in part by the International Cooperation Administration and the State Department.

1) Excluding Ship Operations.

International Cooperation

It is clear that, as in other sciences, a very large part of the pioneering research and new ideas concerning the oceans must come from individual scientists or small groups working independently. But international cooperation in work at sea is essential in several kinds of marine research and should also greatly facilitate surveys of the ocean floor and of the waters.

There is at present a high level of international cooperation among physical and chemical oceanographers of different countries resulting from the International Geophysical Year. This cooperation should be maintained and broadened throughout all aspects of the marine sciences, particularly including biology. To this end, the Committee recommends:

1. The United States through the National Science Foundation should give its proportionate share (amounting to perhaps $20,000 per year) of financial and other support to the Special Committee on Oceanic Research of the International Council of Scientific Unions. The Committee on Oceanography has been designated as the United States National Committee for this long-range cooperative program.

2. Grants should also be sought from foundations and governmental sources to support special projects such as the proposed year-long international expedition to the Indian Ocean by covering the increased expenses to United States' oceanographic institutions and by making the participation of other countries possible. Special funds needed for the Indian Ocean project are estimated at about $2 million.

3. An intergovernmental conference of the maritime countries should be called, after suitable preparation, to discuss means by which the governments can cooperate in increasing man's knowledge of the oceans. Specifically, agreements should be sought regarding the means of carrying out ocean-wide surveys, including allocation of responsibility to different countries, intercalibration of techniques, and free exchange of data. It would be expected that the United States' proportion of this international responsibility for surveys would be about the same as its proportion of financial responsibility for support of United Nations agencies. This conference

should be a first step toward the establishment of a World Oceanographic Organization; a United Nations specialized agency corresponding to the World Meteorological Organization.

4. In the study and conservation of the living resources of the sea, regional international organizations, such as the various international fisheries commissions, have proven effective.

In developing formal intergovernmental cooperation in the marine sciences, the Federal Government should give special emphasis to the establishment and adequate support of such regional organizations, and should seek to broaden their charter to allow an integrated research program on all aspects of a particular oceanic region.

5. In order to increase the effectiveness of cooperation between United States marine scientists and laboratories and marine scientists in other countries, the United States State Department should be prepared to assist positively, sympathetically and promptly in facilitating research ship operations and the exchange of information, persons, equipment and supplies.

6. The need for increased protein foods from the sea is especially urgent in under-developed countries. The International Cooperation Administration in its programs of technical assistance should give greater emphasis to marine resources surveys and to research projects and training programs in the marine sciences. The Federal Government should also encourage United Nations specialized agencies such as UNESCO and FAO in their efforts to aid under-developed countries to achieve greater utilization of marine resources. The funds needed for both these purposes have not been budgeted separately in this report but are included in the budget for Ocean Resources studies.

Budget and Operations

The total recommended budget for the period 1960-1970 broken down by category and agency is given in Tables 17 and 18. It should be emphasized that although the budget includes the capital costs of ships involved in strictly military research and development, it does not include the other costs which are involved in such work.

Concerning the actual funding and operations, the Committee recommends:

1. A higher percentage of longer term funding must be made available in oceanographic research. Past funding has been inefficient, and has held back much longer term imaginative research. A reasonable portion (30 to 50%) of the annual operating budget should include 5 year money which is refreshed annually. Existing laws permit allocation of many funds on a five year basis. The military is accustomed to making long term commitments of 5-10 years when they adopt a new weapons system and it is equally essential that they make long term commitments for research.

2. Administrators of research and laboratory directors must have a higher percentage (25- 50%) of their funding free to spend on those good research problems which emerge without the benefit of planning.

3. Government organizations which presently fund or carry on extensive research and development in oceanography should continue to do so in the field of their special interests. For example, the Navy, the Atomic Energy Commission, and the Bureau of Commercial Fisheries all have their own important oceanographic problems. It is recommended that each bureau and organization sponsor and finance much of the research which it needs to meet the demands of its present and future objectives. Any duplication of effort which might be involved appears trivial compared to the value of insuring that scientists are in close touch with changing bureau problems.

4. There will still remain a need for a great deal of research which should be funded by the National Science Foundation. This agency should carry a much heavier portion of the long term basic research in the nation. A reasonable percentage of grants should be made to individuals and a reasonable portion should be allocated for long term funding of institutional activities such as vehicles, facilities and major expeditions.

5. Foundations, states and industries should take an active part in the support of marine research. Their support is particularly valuable in new and unusual research programs, in filling technological gaps and through appropriate assistance insuring that private laboratories and academic groups do not become solely dependent on Federal assistance.

Table 17

Summary of Budgets for New Oceanographic Activity[1)]

(millions of 1958 dollars)

Year	Education and Manpower	Ships	Shore Facilities (Research)	Shore Facilities (Surveys)	New Devices	Radioactivity[2)] in Oceans	Resources	Total
1960	0.80	39.80	1.50	0.76	7.40	3.08	5.02	58.36
1961	0.80	40.45	2.70	1.52	9.50	2.95	6.71	64.63
1962	0.80	45.30	3.90	3.00	9.60	4.35	5.43	72.38
1963	0.80	35.95	6.60	4.50	10.90	2.95	8.52	70.22
1964	0.80	33.65	10.50	6.00	10.50	2.95	7.55	71.95
1965	0.80	29.00	12.60	7.50	10.50	2.95	10.58	73.93
1966	0.80	20.55	13.50	8.26	10.50	4.39	10.93	68.89
1967	0.80	10.45	13.20	8.26	10.50	2.95	10.75	56.91
1968	0.80	10.45	13.20	8.26	10.50	2.95	10.92	57.08
1969	0.80	10.45	13.20	8.26	10.50	2.95	10.90	57.06
Total	8.00	276.05	90.90	56.32	100.40	32.43	87.31	651.41

1) Not including special funds for basic research projects involving extensive international cooperation such as the proposed year-long international expedition to the Indian Ocean (estimated cost: $2 million).

2) Plus ship time charges of $11.70 million to be subtracted from other categories.

Table 18

2) Plus ship time charges of $11.70 million to be [illegible]

Table 18

Summary of Budget for New Oceanographic Activity by Agency[1)]

(millions of 1958 dollars)

Year	Navy[2)]	C and G S	B of C F	M A	N S F	O of E	A E C	B of M	Total
1960	28.78	5.83	7.97	5.45	6.40	0.50	3.08	0.35	58.36
1961	28.83	6.09	13.86	3.80	8.35	0.50	2.95	0.25	64.63
1962	30.40	9.75	12.83	1.65	12.65	0.50	4.35	0.25	72.38
1963	33.80	8.70	12.42	--	11.60	0.50	2.95	0.25	70.62
1964	35.22	9.30	11.75	--	11.98	0.50	2.95	0.25	71.95
1965	32.68	9.20	15.03	--	13.32	0.50	2.95	0.25	73.93
1966	27.45	9.88	12.38	--	14.08	0.50	4.35	0.25	68.89
1967	20.36	6.43	12.20	--	14.22	0.50	2.95	0.25	56.91
1968	20.36	6.43	12.37	--	14.22	0.50	2.95	0.25	57.08
1969	20.36	6.43	12.35	--	14.22	0.50	2.95	0.25	57.06
Total	278.24[3)]	78.04[3)]	123.16[3)5)]	10.90	121.04[3)]	5.00	32.43[4)]	2.60	651.41

1) Not including special funds for basic research projects involving extensive international cooperation such as the proposed year-long international expedition to the Indian Ocean (estimated cost: $2 million).

2) Not including military Research and Development operations.

3) Less payments by AEC totaling $11.70 million for ship time.

4) Plus $11.70 million for ship time, averaging $1.17 million per year.

5) Includes recommended expenditures by the International Cooperation Administration and the State Department, for projects involving international cooperation and technical assistance to other countries.

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*Committee on Oceanography Members.

V. Panel on Radioactivity in the Oceans

(This group continues to be active as the Committee on the Effects of Atomic Radiation on Oceanography and Fisheries of the National Academy of Sciences' Study of the Biological Effects of Atomic Radiation. It responds to inquiries from but is not officially a part of the Committee on Oceanography.)

Howard Boroughs, Instituto Interamericano De Ciencias Agricolas
Dayton Carritt, The Johns Hopkins University
Walter Chipman, Bureau of Commercial Fisheries
Harmon Craig, Scripps Institution of Oceanography
Lauren Donaldson, University of Washington
Richard Fleming, University of Washington
Richard Foster, General Electric Company
Edward Goldberg, Scripps Institution of Oceanography
John Harley, U. S. Atomic Energy Commission
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Sea Disposal of Low Activity Effluent

by

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1. Foreword. The experiments (Exercise Mermaid) described in this report were performed from August to November 1956 because of the proposal to discharge mildly radioactive liquid effluent, arising at the new Atomic Energy Establishment at Winfrith Heath, into the sea off the Dorset coast. The experiments were somewhat similar to those carried out off the coast at Windscale in 1947. (Operation Seamuts). (1)

It is proposed to convey the effluent from the Winfrith Heath site to the coast by buried pipelines and thence out to sea. After considering engineering aspects, amenities and fishing interests, Arish Mell was regarded as the most suitable point on the coast for commencing the under-water pipeline. Distances ½, 1, 2, 3 and 5 miles (points O_1 to O_5) south of Arish Mell were examined as possible outfalls.

2. Objectives of experiments. Experimental work at sea was undertaken between the 17th August and 18th November, 1956. The main objects of the experiments were: (a) To determine the rate of dilution of a tracer dye by sampling and analysis for varying weather and tidal conditions, (b) To measure the temperature and salinity at various positions and depths with a view to determining any significant gradient capable of influencing dilution rates. (c) To supplement the Admiralty data on tidal streams by making measurements east of Arish Mell Gap. (d) To sample marine life and deposits from the sea-bed for study by the Ministry of Agriculture, Fisheries and Food, (e) To study the contour of the sea-bed.

Results from experiments on these lines should indicate: (1) The rate of dilution of radioactive solutions discharged into the sea and the effective transverse and longitudinal diffusion coefficients. (ii) The best state of

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* U.K. Atomic Energy Authority, A.E.R.E., Harwell.

(1) Seligman, H. The disposal of Waste Products in the Sea. Int. Conf. on the Peaceful uses of Atomic Energy A/Conf. 8P/ 418 (1955)

tide for the discharge to yield high rates of dispersal and removal from the area. (iii) The minimum length of pipeline to ensure a high dilution rate and to preclude excessive build-up of radioactive material in fishing or lobster-catching areas or on the shore. (iv) The permanent concentration of radioactive effluent which would be set up by the daily discharge of a given quantity from the proposed site at Winfrith Heath. (v) Limitations on discharge due to the fauna and mineral deposits on the sea-bed. (vi) The obstacles which would be encountered in laying a pipeline.

3. Geography of the area. Arish Mell Gap is about 10 miles east of Weymouth and 10 miles west of Swanage, as shown in Figure 1 which is a replica of the Admiralty Chart for this region. The surrounding sea area is roughly triangular and is bounded on the south by a line drawn from Portland Bill to St. Alban's Head; the shore provides western and northern boundaries. Suitable pipeline approaches are rare since most of the coastline in this area consists of cliffs. Apart from the beaches around Weymouth the sea is several fathoms deep 100 yards from the shore; the sea-bed then dips more gradually and is approximately 15 fathoms deep 2 miles offshore, but there are some relatively shallow areas, e.g. Lulworth Banks. The sea bottom is mostly rocky with sand in the hollows. The only sandy beaches are at Weymouth, implying that here alone the currents are insufficient to prevent deposition of small solid particles. The total area of the sea triangle is about 200 km^2 which, with an average depth exceeding 18 metres, yields a volume greater than 3.6 km^3. Thus, one tonne of soluble effluent uniformly distributed in this volume would have a concentration less than 3×10^{-10} g. per c.c.

4. Survey of the sea-bed contour. The shaded sector in Figure 1 represents the area of sea-bed surveyed, by arrangement with the Department of the Hydrographer of the Admiralty, by H.M.S. Scott in September, 1956. Further echo-soundings provided detailed information about a rock barrier across the mouth of Worbarrow Bay. Diving operations by H.M. Underwater Development Establishment provided a close-up view of the rock barrier. (See Figure 2)

5. Sea bed fauna and sediments. Scientific Staff of the Ministry of Agriculture, Fisheries and Food have obtained and examined samples of sea-bed fauna and sediments. These have been tested for uptake of radioactive material and the results will be used by the Minister in deciding the initial authorisation for discharge of effluent.

6. Winds. An analysis of the wind force indicates less than force 3 for at least 50 per cent of the time from April to September; for the rest of the year the wind is likely to be less than force 3 for only 25 per cent of the time and is predominantly from the south-west.

7. Tides. Tidal streams are of prime importance in a study of the dispersal of effluent at sea; the tides may be modified by winds exceeding 10 knots. In this area there is a double tide at Weymouth and Portland. High water at Portland is about one hour later than high water at Devonport (to which Admiralty tidal data are referred) and is followed by a first low water after $4\frac{1}{2}$ hours and a second 4 hours later still; these intervals vary

somewhat between spring and neap tides. The tidal rise and fall is small, being 7 ft. at springs and 3 ft. at neaps. On the other hand, the tidal stream velocities are considerable; they approach 7 knots at springs in the Portland and St. Alban's Races. Two miles south of Arish Mell Gap the velocities are 2.5 knots at springs and 1.2 at neaps, which are about double the corresponding values in the Windscale discharge area.

The Admiralty chart includes tables of tidal stream velocities and directions at various points for each hour of a tidal cycle. It is assumed that the flow during springs is parallel to, and double the magnitude of, that during neaps. Examination of these tables show that the vector sum of the tidal stream velocities during a tidal cycle is not zero, and in particular that for the points A, B, D (see Figure 1) this nett drift is shoreward, as shown in Table I (for spring tides).

TABLE I

Admiralty Standard Point	Oscillatory Amplitude (parallel to shore) (Sea Miles)	Mean shoreward residual drift in $12\frac{1}{2}$ hours (Sea Miles)
A	7	1.5
B	10	4.5
D	12	8

The present experiments have shown that shoreward drift persists at all depths and thus, since water cannot pile up indefinitely on the shore, it is necessary to seek an explanation.

Inspection of the Pocket Tidal Stream Atlas[2] shows that there is a southerly drift along the east coast of Portland at nearly all phases of the tide and also makes evident the development of a large eddy around the Shambles soon after the eastward set of the drift past the Bill; there is a similar eddy to the west of Portland Bill on a west-going tide. The shoreward drift from south of Arish Mell is a consequence of the eddy, since water which is sucked into the main English Channel tidal stream along the east coast of Portland must be supplied by a shoreward drift elsewhere. It has been calculated that the total outward flow of water between the Shambles and Portland is about 0.35 $km^3\ hr^{-1}$ in one tidal cycle; this means that, on average, there is an interchange of the main bulk of the water in the triangle with that of the Channel in 12 hours at springs or 24 hours at neaps, although it would take much longer to interchange the water near the shore.

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(2) Approaches to Portland - Pocket Tidal Stream Atlas

Hydrographic Department, Admiralty.

Since the tidal atlas (2) does not provide data to the east of Arish Mell the experiments included observations of the drift of buoys, without drogues, from the points M_1 - M_4. The results are not claimed as accurate hydrographic data but they were not contradicted by any of the remaining experiments. Table II records the oscillatory amplitudes and mean drifts at springs for these points.

TABLE II

Reference Point	Oscillatory Amplitude (Sea Miles)	Mean drift in 12½ hours (Sea Miles)
M_1	7.5 WNW - ESE	4.5 NNW
M_2	11 WNW - ESE	10 NW
M_3	10 WNW - ESE	9 WNW
M_4	13.5 WNW - ESE	17 SSE

Note that the mean drift at M_4 is seaward and nearly opposite to the drifts at M_1 - M_3. The observations at M_4 agree with the hypothesis of a right handed eddy, to the west of St. Alban's Head, analogous but in the opposite sense to the Shambles eddy. The westerly components of drift at M_1 - M_3 indicate a complicated secondary eddy near the Kimmeridge Ledges and this is also rendered not unlikely in view of the rapid fluctuation of depth off these ledges.

Using the data from the Pocket Tidal Stream Atlas(2), predictions were made of the course of a drifting buoy released at various phases of the tide from the points O_3 - O_5. A specimen plot is shown in Figure 3. It became evident that after release on west-going tides the general tendency would be to drift at first shoreward and ultimately towards Portland Bill and the open sea in periods from 12 to 36 hours. This statement was confirmed experimentally by the plastic envelope results which are illustrated in figure 4 (Section 23). On east-going tides there is a similar but less pronounced tendency to reach the open sea along the western coast of St. Alban's Head.

8. Temperature and salinity measurements. Since variations of salinity and temperature would be expected to affect the rate of mixing of an effluent discharged into the sea, samples were taken with a Nansen-Patterson sampler from different depths at 50 widely distributed points in this sea area. Uniform temperatures and salinities were found in all the analyses, agreeing with the absence of large rivers and of prolonged calm weather.

9. The mechanism of dispersion. The principal object of the present work was to investigate the speed of dispersal of soluble effluent and, in

(2) Approaches to Portland - Pocket Tidal Stream Atlas
Hydrographic Department, Admiralty.

doing so, to compare with the results of Operation Seasuits.[1] The amount of damage to organisms exposed to radioactive effluent depends on the dose received and hence it is important to be able to estimate the time-mean concentration at different distances from the outfall for a given quantity and rate of effluent discharge.

The dispersion process consists of two phases, particularly after a discharge on the sea-bed. In the first phase the dye spreads in three dimensions until the vertical spread is more or less complete; at this point the second phase begins and the spreading is now only longitudinal and lateral. A discharge at the sea-bed, where water moves more slowly than on the surface, results in a lag of the centre of distribution behind the mean current during the first phase but thereafter the centre will move with the velocity of the depth-mean current.

Horizontal dispersion is effected in two ways which can be considered independently. The first is due to regular fluctuations of the tidal stream direction throughout a tidal cycle and the second to turbulent diffusion.

10. Effect of Regular Fluctuations in Tidal Stream Direction. The centre of the distribution is carried along at the mean drift velocity of the current. In the neighbourhood of Arish Mell the tides are such that the effluent does not, in general, return after completion of a tidal cycle and it does not follow the same track when released at different phases of the tide. Thus if released continuously the trail of effluent sweeps over an area. If the tidal stream is periodic this area is bounded by an envelope. The effective time mean concentration would become infinite near this boundary in the absence of transverse eddy diffusion whose effect is therefore chiefly of importance in this region.

The effective dilution due to movement with the mean drift has been considered mathematically. In order to apply this analysis an accurate knowledge of the tidal streams is required, and some of the experimental effort was applied to supplementing Admiralty data.

11. Factors Affecting Turbulent Diffusion (Eddy Diffusion). The diffusion process is analogous to the spreading of smoke in the atmosphere. It is many orders of magnitude more rapid than molecular diffusion. In molecular diffusion the spreading is due to the differing motions of the individual molecules. In eddy diffusion it is due to the differing motions of the individual eddies. As a consequence, the original compact distribution is drawn out into long streaks and filaments. When sufficiently large local concentration gradients have been thus set up they may be smoothed out by molecular diffusion, but on the whole this will play an almost negligible role. The eddies giving rise to turbulent diffusion are of all sizes, though an upper limit is probably set by the depth.

The distribution of current with depth is determined by the diffusion of momentum to the sea bottom. Since in turbulent flow momentum is also

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(2) Approaches to Portland - Pocket Tidal Stream Atlas
Hydrographic Department, Admiralty.

transported by eddies it is reasonable to suppose that the laws governing the transport of matter and momentum are similar. Following this analogy it is possible to predict the duration of the first phase, during which vertical spreading becomes nearly complete. (See Section 13). For the point O_3 it is of the order of half an hour, or, more strictly speaking, it will last until the effluent has drifted about a mile downstream. The turbulence is likely to be affected by:

(a) The mean tidal current and depth. The Reynolds number is equal to the product of the depth and the depth-mean current divided by the kinematic viscosity and is of the order 10^7 for this area; this value implies fully turbulent flow. The amount of turbulence is likely to increase with the Reynold's number, and hence with the current and depth. In addition the space available for vertical spreading is proportional to the depth.

(b) The roughness of the sea-bed, provided it is not too extreme, may be assessed by a parameter Z_o which is called the "roughness length". It is well known in turbulent flow the current at a small, but not too small, height Z above a rigid boundary is proportional to log Z/Z_o. Dye discharges at O_3 verified this law and a value Z_o = 2 mm was found (see Section 19).

(c) Wind near the surface of the sea will, when sufficiently strong, increase the turbulence by raising waves. Experimental work was difficult at wind forces greater than 5 - 6 but calm water is the most important case to consider since dispersion is then less rapid, other things being equal.

(d) Variations of temperature and salinity may inhibit the turbulence if they can produce a negative density gradient. This would result from a negative salinity or a positive temperature gradient. The latter could be caused by bright sunshine in calm weather and could possibly be self-sustaining. These conditions never occurred during this study but the effects must be borne in mind.

(e) Proximity of the shore will alter the direction of currents, particularly if the shore is not straight, and breaking waves will increase the turbulence.

12. Quantitative Analyses of Dye Experiments. Both short and continuous discharges (Sections 20 and 21) were made with known quantities of fluorescent dye and the ships used carried out a sampling plan to determine the dilution. At this point it is worth discussing what can be learnt from such experiments.

(a) Rate of dilution after short discharges. Short discharges were mostly made on the sea-bed and the behaviour of the resulting patch was studied by sampling and locating and plotting the track of its centre. Dye was seen on the surface after intervals of a few minutes to half an hour following the mean release time. The patch had an irregular shape and was elongated in the direction of the tidal current. Irregular readings persisted for several hours but smaller variation was found by averaging the concentrations at various depths.

Following the procedure at Windscale the concentrations near the centre were plotted against time on double logarithmic paper, and it was found that after about half an hour maximum concentration diminished roughly inversely as the time: there was little positive evidence that it diminished more rapidly than this. If the depth-mean relative concentration $\bar{C}$ is defined in units of 10^{-9} g cc per tonne discharged i.e. of tonnes per cu km per tonne discharged and t is time in hours after discharge, then the maximum concentration was:-

$$\bar{C}_{MAX} = A_2/t$$

The experimentally determined value of A_2 (see Table III) varied between 1300 and 180 with a median value of 600, which is very close to the Windscale value of 750.

Since relative concentration, as defined above, has the dimensions of an inverse volume, dimensional considerations suggest that the maximum concentration may be better represented by a formula of the type

$$1/\bar{C}_{MAX} = H^2(S + S_0)/\alpha = (S + S_0)/\gamma_{MAX}$$

where H is the depth, S the distance travelled by the centre of the patch, S_0 a constant distance to allow for the different rate of spreading in the early phases, α a dimensionless number, and γ_{MAX} a constant with the dimensions of an inverse area. The parameters S_0 and $1/\gamma_{MAX}$ can be found by plotting the dilution $1/\bar{C}$ against S. The points should all lie above a straight line of slope $1/\gamma_{MAX}$ with intercept $-S_0$ on the S axis. This linear law was found to be reasonably well satisfied. A specimen plot is shown in figure 5.

The values of γ_{MAX} (Table III) obtained on the eight best runs, which were made at O_3 and O_4, varied between 1100 and 190 km^{-2}, with a median value of 665, which should be compared with the Windscale value of 405. The parameter S_0 required to make the best fit varied between ± 1 km.

At both O_3 and O_4 the depth was approximately 28.5 meters, giving a value of α varying between 0.90 and 0.155 with a median value of 0.54. The considerably lower median value (0.11) derived from an analysis of the Seanuts results is probably due to differences in experimental technique and is anyway less reliable. The dimensionless number α is likely to be influenced by such factors as the ratio of the roughness length to the depth, the tidal stream velocity to the velocity of rotation of the earth, and the weather conditions.

(b) Diffusion Coefficients. The fact that the dilution is roughly linear with the time after sufficient interval has elapsed for spread between top and bottom to be complete suggests an analogy with two dimensional molecular diffusion, and the phenomenon may be represented by the introduction of effective longitudinal and transverse eddy diffusion coefficients J_s and J_n, which may be defined in terms of the rate of growth of the mean square length and breadth of the patch. These quantities have

the dimensions of a length times a velocity, which suggests the formulae

$$J_s = \bar{U}L_s = \bar{U}Hl_s$$

$$J_n = \bar{U}L_n = \bar{U}Hl_n$$

where L_s and L_n are characteristic lengths, $\bar{U}$ is the depth-mean current, H the depth, and l_s, l_n are members. The lengths L_s and L_n may now be defined by the formulae

$$\langle \Delta X^2 \rangle = \iint \bar{C}\ \Delta X^2 dX dY / \iint \bar{C} dX dY = 2L_s(S + S_0)$$

$$\langle \Delta Y^2 \rangle = \iint \bar{C}\ \Delta Y^2 dX dY \iint \bar{C} dX dY = 2L_n(S + S_0)$$

where ΔX, ΔY are distances from the centre of the patch measured longitudinally and transversely, and the integration is over the whole patch. For a continuous discharge L_s cannot be determined, whilst L_n is found by a single integration across the patch.

In the ideal case the concentration near the centre of the patch should be given by the Gaussian formula

$$C = C_{MAX} \exp - \tfrac{1}{4} (\Delta X^2/L_s + \Delta Y^2/L_n)/(S + S_0)$$

where $C_{MAX} = \gamma MAX/(S + S_0) = 1/4\pi H\sqrt{L_s L_n}\ (S + S_0)$. Hence the patch should be elliptic with an axial ratio $\sqrt{L_s/L_n}$. The lengths L_s and L_n may be determined either by determining $L_s L_n$ from the formula $L_s L_n = 1/4\pi H\gamma MAX$ and $\sqrt{L_s/L_n}$ from observation of the shape of the patch, or directly from the formulae for ΔX^2 and ΔY^2, in which case the results can be checked by re-estimating the total quantity of dye from the formula

$$M = 4\pi H\gamma MAX\sqrt{L_s L_n}$$

M should be close to unity.

The latter procedure was employed where possible. A rather complicated technique had to be used in reducing the observations so as to compensate for the growth and movement of the patch whilst samples were being taken, and it had to be assumed that the positions of the ships relative to the centre of the patch were sufficiently varied to permit the integrals to be replaced by sums over the sampling positions. Nevertheless the values of M obtained on the best runs, though generally greather than unity, were sufficiently close to unity to give some confidence in the values obtained for L_s and L_n.

The values of L_s obtained by this means varied between 620 and 5 metres with a median of 34.5 metres. The values of L_n were between 5.5 and 0.4 metres, with a median of 2.15 metres. Assuming a depth of 28.5 metres, the dimensionless numbers l_s and l_n are then 1.86 and 0.116. Again, assuming an average current of one knot, i.e. 51 cms / sec., the corresponding values of J_s and J_n are 1.8×10^5 and 1.1×10^4 $cm^2\ sec^{-1}$ respectively.

The longitudinal spreading represented by L_s is due to a combination

of direct longitudinal eddy diffusion and the "shear effect." Generally the current will be stronger near the surface and hence dye which has spent most of its time near the sea-bed will lag behind the rest. This effect, which is likely to predominate in calm weather, produces long narrow patches; observation supports this statement. Furthermore, if the currents are not parallel at all depths the "shear effect" will also contribute to lateral diffusion.

Vertical mixing increases with turbulence and transverse mixing will probably increase in proportion. On the other hand the increased vertical mixing tends to reduce the "shear effect." The patch should, therefore, become less elongated with increasing turbulence and the variation in γ_{MAX} should be less pronounced; again, observation appeared to confirm this.

(c) Continuous discharges are simpler to analyse than short discharges since, apart from variations in the tide, the pattern is statistically stationary. They were made at O_3, using the same amount of dye as in the short discharges, but lasted for three to four hours and gave rise to a "plume" of dye solution. The time-mean concentration at a given point cannot be found directly from the data for a short discharge but can be obtained from measurements on a continuous discharge. Diffusion theory implies that sufficiently far downstream the concentration along the centre line of the trail should be proportional to $L_n^{-\frac{1}{2}}(S + S_0)^{-\frac{1}{2}}$ and the breadth of the trail should vary as $L_n^{\frac{1}{2}}(S + S_0)^{\frac{1}{2}}$; the trail should thus have a parabolic outline.

An analysis of a set of aerial photographs of the plume confirmed the parabolic law and yielded a value of L_n equal to 1 metre, which agrees quite well with the measurements on short discharges described above. An analysis (on a different occasion) of the transverse dye distribution 800 metres downstream from the discharge point gave a value of 0.4 metres if it be assumed that S_0 is zero.

(d) General remark. When consideration is given to the regular variation of the tidal stream during a tidal cycle it is found that transverse diffusion is only of importance in determining the time-mean concentration from a continuous discharge near the edge of the area swept out by the trail; when both effects are considered together it can be shown that the maximum time-mean concentration near this boundary varies as $L_n^{-\frac{1}{4}}$, and thus L_n need only be known approximately in order to predict this quantity.

13. Vertical mixing during the first phase. It is not unreasonable to assume that matter and momentum are diffused in the same manner, since both are diffused by the same eddies. The downward diffusion of momentum determines the frictional drag on the sea-bed and the time-mean velocity distribution. The proportionality between the logarithm of the height above the sea-bed and the velocity, near to the sea-bed, implies that the vertical diffusion coefficient K_{ZZ} is proportional to Z. Two models have been assumed, in which K_{ZZ} is equal to $0.16\ Z\ [\partial U/\partial(\ln Z)]_{Z\to 0}$ and to $0.16\ Z\ (1 - Z/H)\ [\partial U/\partial(\ln Z)]_{Z\to 0}$ respectively: the latter is suggested by noting that in calm weather eddies cannot cross the surface, and hence

K_{zz} must vanish there. These models enable predictions to be made about the vertical distribution of dye provided the current distribution near the bottom is known. Measurements 800 metres downstream on the vertical distribution of dye in the plume from the continuous discharge mentioned above were in reasonable agreement with the second model, which also predicts that vertical mixing should be about 90% complete at double this distance downstream.

14. Choice and development of experimental techniques. The experimental methods used in the present study were influenced by the prior experiments at Windscale(1) in which a fluorescent dye was discharged into the sea and traced by sampling. The Windscale experiments enabled the Minister of Supply to agree with the other Ministers concerned the amount of radio isotopes which could be discharged into the sea off the Cumberland coast without in any way affecting residents, visitors or local industries. The very considerable experience at Windscale since that time in sampling and testing permits the results obtained in practice to be correlated with the predictions made from the dye experiments and affords a sound basis for the interpretation of similar trials elsewhere. In the present study the main effort was devoted to investigating the distribution and rate of dispersal of a fluorescent dye discharged from the points O_1 to O_5, using 1 ton of dye in 1000 gallons of water.

15. Experimental equipment.

(a) Choice of tracer dye. The choice appeared to lie between fluorescein which had been used at Windscale and Amino-G-Acid (2-naphthylamine -6:8 - disulphonic acid). The fading of fluorescein in sunlight would have meant working at night and analysing the samples aboard the vessel. Amino-G-Acid, on the other hand, has good light-fastness, is less than a third the price of fluorescein and more readily available; it is also less prominent if washed ashore in a holiday-making area; it was therefore used in most experiments but about 10% of added fluorescein made tracking easier.

(b) Ships. Three 75 ft. Motor Fishing Vessels were obtained from the Admiralty, two being fitted with spare fuel tanks for use as containers of dye solutions. These tanks were filled from make-up tanks ashore and were discharged when at sea by means of pumps and flexible weighted reinforced-rubber hose. All ships were equipped for sampling sea water at various depths. These MFVs were supplemented, for inshore sampling, by two 32 ft. motor cutters, equipped only for surface sampling, which were in radio-contact with the MFVs. The MFVs were also equipped with Decca Navigational Aids and automatic track plotters and their positions could thus be reproduced to an accuracy of ± 6 yards.

(c) Sampling equipment. The A.E.R.E. sampler which is a light duty modification of the Nansen-Petterson sampler (see figure 6) was most suitable for samples at all depths below 30 ft; it was raised and

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(1) Seligman H. The disposal of Waste Products in the Sea. Int. Conf. on the Peaceful Uses of Atomic Energy A/Conf. 8/P/418 (1955).

lowered by means of an electrically driven Kelvin sounding winch. Samples from 20 ft. were pumped through a weighted polythene tube and surface samples were obtained in a clean polythene bucket. It was possible to obtain a series of four samples from surface to sea-bed in less than 2 minutes. Considerable spares for samplers and pumps were necessary. Screw-capped polythene bottles in metal crates were used as sample containers.

(d) Buoy and floats. The following of dye patches was assisted by using dan and pellet buoys, with and without drogues, painted wooden blocks, sheets of water-proof paper and polythene envelopes. The buoys were also applied to the study of tidal flow.

(e) Aircraft were used for following dye patches and photographing floating envelopes, and were eventually fitted with Decca track plotters.

(f) Shore facilities. These comprised changing and storage rooms, a laboratory, office and a shed for dye storage and make up. Berths for MFVs and motor cutters were also supplied. Two dye make-up tanks, rubberised internally and provided with motor paddle stirrers, were installed.

16. Dye preparation. Amino-G-Acid solutions were prepared in the make-up tanks ashore. One ton of dye, as received, was treated with sufficient caustic soda to yield the di-sodium salt and then made up with fresh water to 1000 gallons; 8 hours settling was allowed before transferring to the ship's tanks. The density of the solution was 1.13 (sea water 1.035) whereas that of ordinary effluent is only 1.01 - 1.02. The high concentration was used to improve the chances of visual spotting of the dye after discharge and to yield samples of high concentration; preliminary experiments had already indicated rapid dilution of these concentrated solutions. More dilute solutions with a density 1.01 - 1.02 were used on two occasions and in later experiments 10% of fluorescein was added to render the patches more easily visible.

17. Fluorimetric Analysis. It is possible to detect 1 part of Amino-G-Acid or its sodium salt in 10^9 parts of sea water in ultra violet light. An A.E.R.E. Fluorimeter type 1080A was used for measuring concentrations as compared with that of the strong solution from which standards were made by dilution. Details of the method of measurement were already available(3).

18. Estimation of tidal flow. Buoys and other markers have already been mentioned as means of facilitating identification of a dye patch.

In order to study the tidal drift at different depths use was made of drogues attached to the buoys by cable. The drogues consisted of two crossed aluminium sheets firmly clamped together. The most satisfactory equipment consisted of a dan buoy provided with a stout wooden pole to which the drogue (2 sheets 6 ft. x 4 ft.) was attached by $\frac{1}{2}$" stranded cable; these are known as logships.

Shoreward drift from points 0.75, 1.5 and 3 miles south of Ariah Mell

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(3) Hartley, H.E.R. The fluorimetric estimation of traces of 2 Naphthylamine 6;8 Disulphonic Acid in Seawater Chemical Inspectorate, Min. of Supply. W.SI/Memo 62 (1952)

was studied by simultaneous release of 10 ft. logships at each point just before the tide turned to west-going. The logship released at the 0.75 mile point drifted ashore in less than 2 hours whereas the others, after a curved track, drifted west-ward and roughly parallel to the coastline. (See figure 7).

Drift variation with depth was studied at the point O_3 by releasing 5, 30 and 45 ft. logships, allowing them to drift for a known time, retrieving and repeating the whole procedure. It was found that the direction of drift of the 45 ft. logship differed considerably from those of the others when the tide was turning.

The measurements made at points M_1 - M_4 merely indicated surface currents since pellet buoys without drogues were used. The buoy was released at the specified point at a given time and recovered after half-an hour; magnitude and direction of drift were recorded. Experiments were performed to cover the whole of a tidal cycle at all these points.

19. Current measurements with current meters. These measurements were made from the moored vessel during the continuous discharge experiments by a team from the National Institute of Oceanography. Measurements were made in sequence at depths of 5, 10, 15 and 20 metres below the surface by means of a Fjeldstat current meter. Other readings were taken at 1.41, 1.0, 0.62 and 0.31 metres from the sea-bed by means of a special current-meter which has four sets of cup-type vanes, mounted one above another, on a tube attached to a tripod which rests on the sea-bed; revolutions of the cups are counted by a magnetic trip which interrupts an electrical circuit.

The results of this work show a similarity in the detailed nature of the currents at the various depths near the bottom; this implies the existence of eddies near the sea-bed whose vertical dimensions are comparable with the separation between the current-meters, that is, they are of the order of 1 metre.

The velocity profile near the sea-bed was found to satisfy the law

$$U = A \log Z/Z_0$$

although the roughness length Z_0 was rather variable. The weighted mean was 0.2 cms.

From a study of the tidal stream velocities at depths of 5, 10, 15 and 20 metres it is found that the logarithmic law is reasonably well satisfied except when the tide is turning; this implies an appreciable phase difference between the tidal fluctuations near the surface and near the sea-bed.

20. Continuous discharge experiments. One ship, moored at O_3, discharged one ton of dye (18 cwt. Amino-G-Acid + 2 cwt. Fluorescein) in 1000 gallons of water at a uniform rate over 3-4 hours. Two other ships sampled continuously across the plume of dye solution at two distances downstream while an aircraft took an aerial mosaic of the plume from which the shape and width could be measured. The results of this experiment have been

described above.

21. Short period discharge experiments. These are defined as the release of a given quantity of dye at a fixed point and at the sea-bed within a period not exceeding 20 minutes.

The sampling plans varied in detail but were designed to locate the dyepatch and its centre for as long as possible (usually 6 - 7 hours) after the discharge time.

(a) Normal discharges are defined as the release of 1 ton of dye (plus caustic soda) made to 1000 gallons with fresh water. The dilution was found to increase approximately directly with time; dye discharged at O_1 or O_2 tended to move rapidly toward the shore.

The shoreward drift of the dye was never as pronounced as the tidal data would indicate. The points O_3 and O_4 appear satisfactory as outfalls because dispersal of dye is good and the time taken for the patch to approach the shore is usually greater than 12 hours; if discharges are made at slack water before an east-going tide much of the effluent will reach and be thoroughly diluted by the water in St. Alban's Race; at other phases of the tide this effluent is rapidly diluted in the bay and eventually swept into the main channel. Shore and cutter samples have confirmed that little effluent discharged from these points reaches the shore.

(b) Dilute discharges. These consisted in the release of 3 cwt of dye in 1000 gallons in a 20 minute period. As expected these were seen on the surface more quickly than the normal discharges but there was a disadvantage in that the patch could only be seen for 2 - 3 hours. The visibility was improved by replacing 1 cwt of Amino-G-Acid with Fluorescein and this experiment indicated somewhat improved dilution with distance compared with that from a normal discharge.

(c) Surface discharges. A surface discharge of 6 cwt fluorescein made to 1000 gallons with water (same density as sea-water) was used to give a direct comparison with the Operation Seanuts' experiment. On the basis of a concentration time graph the rate of dilution in the Dorset coastal area was clearly greater, on this particular rather stormy day, than it was off the Cumberland coast. The discharge was started shortly before an east-going tide and the dye patch was seen eventually to be rapidly mixing with the water in St. Alban's Race. The path followed by the dye is shown in figure 8, which is partially based on aerial observation.

22. Rate of dilution. The quantitative results of the experiments have been discussed above in section 12, and those for the eight best days are shown in detail in Table III. On a time basis the dilution rates for the Dorset and Windscale experiments are very nearly equal; this result is surprising because of the greater depth and stronger tides in the Dorset experiment. The Windscale results, however, are probably low whereas the Dorset results are high, as is shown by estimating the quantity of dye released from measurements of concen-

trations and size of the dye patch (50% for Windscale and 150% for Dorset). Thus it seems that dilution off Ariah Mell may be about twice as rapid as off Windscale.

23. Surface drifts (polythene envelope experiment). Since it was not easy to trace the dye for more than one tidal cycle it was decided to obtain more information on displacement of water from the triangular sea area by a different method. It was planned to release polythene envelopes containing stiff fluorescent card in batches of 300 at hourly intervals throughout a tidal cycle at the point 03 in calm weather, and to follow their dispositions by aerial photography over several tidal cycles.

Such an experiment should also give information on longitudinal and lateral diffusion and the behaviour of effluent on a calm day.

The envelopes were released from 02.10 to 14.10 on the 16th November and photographs were taken during that day and the morning of the 17th. On the 17th the aircraft found only about 12 envelopes floating off the east coast of Portland while observers on the ships saw a few more about 2 miles off shore between Portland and Ariah Mell. (See Figure 4). On the 16th, however, the aircraft spotted a large number of envelopes in St. Alban's Race confirming that, under favourable conditions, the Race can be relief upon to provide rapid dilution. This is also supported by observations on the surface discharge of fluorescein (section 21) and by a discharge made at the edge of St. Alban's Race just as the tide was turning from east to west going; the eastern edge of this last discharge, viewed for nearly 2 hours, was gradually bent seaward and became very diffuse.

The aircraft was fitted with an aerial survey camera and a Decca track plotter. It was able to identify groups 7, 6 and 5 between 08.45 and 09.00 but the earlier groups had moved already into St. Alban's Race. At 13.15 on the same day the aircraft could only identify group 7 and subsequent groups; group 12 was photographed on six occasions between 13.10 and 15.10. Analysis of these photographs showed that the diffusion lengths, i.e. $L_x = 0.74\ t^{0.38}$ and $L_n = 0.11\ t^{1.57}$ metres, were considerably smaller than those yielded by dye experiments, as might be expected since only surface drift is involved. The failure to find many envelopes on the 17th indicates the rapid rate of dispersal and removal of effluent from the area.

24. Discharge of aqueous radioactive effluent to the sea from Winfrith.

24.1. General. Before permission is granted for the discharge of radioactive effluent into the sea off the Dorset coast the results of the dye experiments will be studied in detail by the Ministers of Housing and Local Government and of Agriculture, Fisheries and Food who are responsible for authorising such discharges. In addition any features peculiar to the neighbourhood will be considered and the extensive experience gained at Windscale with experimental discharges of radioactive material will be taken into account.

Under the terms of the Atomic Energy Authority Act of 1954, it is laid down that, although the responsibility for issuing authorisation for discharge rests with the two Ministers, the United Kingdom Atomic Energy Authority must, in addition, ensure that no hurt is caused by ionising radiation resulting from the discharges of radioactive material from any of its premises.

The International Commission on Radiological Protection has recommended basic maximum permissible levels of activity for occupational exposure to radiation and also the corresponding maximum permissible concentrations of radioactive substances in air and water. It is the practice in Great Britain to reduce these levels by at least a factor of ten if they are to be applied to the general public.

In considering radioactive discharges not only is it essential to know the fate of the discharged activity but it is necessary also to consider how discharges, maintained over a long period, may affect mankind.

In the case of sea discharges the ways in which the general public may be affected are: (a) Bathing in active sea water. (b) Lying or walking on adjacent shores. (c) Handling contaminated fishing gear. (d) Consumption of contaminated fish. (e) Consumption of sea weed or from other uses of sea weed - for example as a fertiliser. (f) Swallowing active sea water or sand or absorbing either of these through damaged skin. (g) Breathing active sea spray, salt or dust from the shore.

There is, in addition, the known property of sea bed, sea sand, fish and sea weed etc. to concentrate the activity of the sea water and it must be ensured that such concentrations do not attain hazardous levels. Much work has been done on this problem in Great Britain and it is possible to specify the activity level to which the concentrating media may be raised with safety. Such a specification must, of necessity, take into consideration circumstances peculiar to the area, for example, local industries and habits of local residents. A survey has been carried out in Dorset and this, together with Windscale experiences, enables an estimate to be made of the amount of radioactive material which can be discharged with safety.

24.2. Factors governing discharges

24.2.1. Dispersion. The results of Exercise Mermaid show that the dispersion of effluent in the sea off Arish Mell will be at least as rapid as off Windscale. Existing tidal information and that obtained during the Exercise show that there will be greater variability in the direction of travel of a patch of effluent. The average concentration resulting from regular discharges of waste should, therefore, be significantly less than that resulting from similar discharges at Windscale. If, therefore, the figures obtained from the Windscale monitoring programme, for the activity levels in sea bed, sea shore, sea weed and fish resulting from a discharge rate of 1 curie per month, are used as a basis a factor of safety will be invoked. Such safety factors are not unreasonable where public health is concerned.

24.2.2. Sea-bed and Fishing Gear. Although the sea-bed is largely rocky off the Dorset coast, there are areas where sand predominates, and these are of particular importance to the lobster fishing industry. A local survey in Dorset has established the length of the lobster fishing season and the time spent by the fishermen in handling gear in and out of season. From this it emerges that a small minority could spend approximately 1670 hours in a year in close proximity to contaminated gear.

Windscale experience shows that the activity of trawls used in the area is approximately one-twentieth of that of the sea-bed. It is expected that lobster pots will take up a somewhat higher proportion and a figure of one-tenth has been suggested. If the activity of the lobster pots is restricted to $1.6 \times 10^{-3} \mu c/g$, then it can be demonstrated that the gear can be handled with safety for periods much greater than 1670 hours. Accepting this activity level it follows that the activity of the sea-bed should not exceed $1.6 \times 10^{-2} \mu c/g$.

24.2.3. Sea Shore. At Windscale the mean activity of the sea shore is lower than that of the sea bed near the effluent outlet by a factor of about 30 and hence it can be assumed that the mean water activities have the same ratio. Off Arish Mell the flow of the tidal stream is more complicated than off the Cumberland coast, there is a net shoreward drift and the ratio of the mean concentration near the discharge point and at the shore depends greatly on the position of the discharge point and on the time of discharge relative to high water. The direct measurement of the ratio has been complicated by the presence of fluorescent contaminants in the water near the shore but even if the discharge point is at two miles from the shore it appears that the ratio must be taken to be as low as three or four if it is proposed to discharge at any time during a tidal cycle. It must therefore be assumed that the concentration at the shore in Dorset will be relatively ten times greater than at Windscale and this factor must be taken into account in determining the permissible discharge. The permissible activity on the shore must not exceed that found by many years' experience to be harmless at Windscale ($2.5 \times 10^{-2} \mu c/g$. This means that anyone may safely spend 100 hours a year at the low water mark on a beach contaminated consistently at this level.

24.2.2. Sea weed. There is no collection of edible sea weed from the Dorset coast and very little other use for this material. The maximum permissible activity of the weed is therefore governed by the radiation level from accumulation of weed and can be taken as the same for shore sand, i.e. $2.5 \times 10^{-2} \mu c/g$.

24.2.5. Fish. The main species of fish of commercial interest off the Dorset coast are lobster and other shell fish. These also assume major importance because of their low mobility and other characteristics resulting in their concentrating activity more effectively than do plaice, the most important fish off

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Windscale. In the calculations made for the safe permissible discharge it is assumed that fish in Dorset will take up a proportion of the discharge ten times greater than at Windscale.

The consumption of lobster flesh in the area is very variable but is high in the case of certain lobster fishermen and their families. A survey indicates that the consumption by a few people may reach 100 g/day. If this figure is accepted the maximum permissible level for the edible portion must be restricted to 5×10^{-4} μc/g.

24.3. Predicted Permissible Discharge. Table IV combines the Windscale experiences with radioactive discharges with the result of Exercise Mermaid and the knowledge of local conditions as outlined above. The Windscale results used are the best estimates of the average activity in the various materials for a regular unit discharge of one curie per month (28 days). They have been obtained from the experimental discharges from 1952 to the end of 1956 and are taken from a summary prepared for the United Nations Scientific Committee on the effects of Atomic Radiation.

Column 2 of the table gives the maximum permissible levels proposed for use off the south coast; column 3 the activity levels to be expected for a discharge rate of one curie per month and column 4 the permissible discharge rate calculated from the data given in the previous columns. All the figures given refer to total β activity.

TABLE IV

	Maximum Permissible Levels (μc/g)	Activity Level (μc/g per c/month)	Maximum Permissible discharge rate (c/month)
Sea bed	1.6×10^{-2}	6×10^{-7}	2.7×10^{4}
Sea shore	2.5×10^{-2}	2×10^{-7}	1.3×10^{5}
Sea weed	2.5×10^{-2}	4×10^{-7}	6×10^{4}
Fish	5×10^{-4}	2×10^{-8}	2.5×10^{4}

It thus appears that a regular discharge of 25,000 curies per month would be permissible off Arish Mell if the release point is two miles out to sea.

It is customary to ask for an interim authorisation for an experimental period during which regular sampling and surveys are carried out to study the affects produced, with discharges of radioactive material. A rate of one tenth of the above figure, i.e. 2,500 curies per month would be acceptable for this purpose and it would be desirable to limit the contribution to the total made by certain isotopes.

25. Summary and Conclusions

(a) The tidal streams off Arish Mell are strong and they vary in direction throughout a tidal cycle. This assists effective dilution.

(b) There is a shoreward drift in the area and very much diluted effluent will approach, but not necessarily reach, the shore particularly if discharged on a west-going tide.

(c) This shoreward drift is considered to be due to the peculiar tidal conditions in the area giving rise to a suction effect off Portland Bill and St. Alban's Head. Whilst the drift may seem a disadvantage it does ensure a greater dilution due to resultant circulation around the whole bay and also diminishes the chance of a local build-up at the end of the pipeline or anywhere in the area.

(d) There is considerable evidence to show that effluent discharged from points 2, 3 and 5 miles from the shore on an east-going tide will reach and be mixed with the water in St. Alban's Race. Later, when the tide turns west, this greatly diluted effluent will be swept out to sea. The above condition applies for the 2 and 3 mile points only if the tidal velocity is high (near springs) and if the tide is running east for a sufficient time. Otherwise the effluent will not reach the Race and will be swept back towards the discharge point in a much diluted state.

(e) It was often found that the dye had a lower rate of flow than was predicted from the Admiralty data which refer to an average speed for depths down to 5 fathoms. This may explain the difference, sometimes found, between the predictions made from buoy experiments and the behaviour of the dye as found during the trials.

(f) The rate of dilution is approximately linear with time but more strictly with distance. Considering only the discharges when fluorescein was used, the maximum concentration at any depth, t hours after discharge ($t>1$), has a value round about $950 \times 10^{9}/t$. When the concentrations are first averaged over all four depths the corresponding value becomes $600 \times 10^{-9}/t$ g/cc. per ton discharged. On a distance basis this latter figure is equivalent to $660 \times 10^{-9}/S$ (where S is in km and $S>1$).

(g) Estimation of the time-mean concentration that will be encountered S km. downstream from the source requires a knowledge of the lateral diffusion coefficient. The value of this derived from the continuous discharge experiment of 17th October 1956, which agrees with the lowest value obtained from the normal discharges, yields a time-mean concentration of $4 \times 10^{-10}/\sqrt{S}$ uc per cc. for a monthly discharge of 1 curie (provided $S>1$ km).

This calculation makes no allowance for variations in the tidal stream direction which will reduce the value considerably. On the other hand it ignores any concentrating effects which have been taken into consideration in compiling Table IV.

(h) Support for the statement that there is a continual displacement

of water from the Portland Bill - St. Alban's Head area by new water from the English Channel is given by the polythene envelope experiment and certain of the dye discharges previously discussed. Further evidence is the lack of any significant build-up of dye in any part of the area throughout the three months of experiment.

(i) The maximum concentration found immediately adjacent to the pipe at the time of the discharge was 56,000 parts of dye in 10^9 parts of sea water. This represents a dilution of 4×10^3 and was obtained under the worst conditions, i.e. slack water. The initial dilution will, of course, be affected by the velocity of discharge from the pipeline, the design of the pipeline diffuser, the specific gravity of the effluent and the tidal speed.

Around the outfall the concentration decreases rapidly as in a plume of smoke. Uniform mixing between top and bottom is practically complete at a distance of 2 km. from the outfall. Thereafter the plot of dilution against distance is linear.

(j) It is instructive to compare the conditions off Arish Mell with those off Windscale. In this way advantage can be taken of the very considerable experience gained with the discharge of radioactive material to the sea in Cumberland.

The higher tidal velocities, the rougher sea bottom, and the greater average depth of water should aid more rapid dilution off Arish Mell.

Examination of the results obtained on the 10th November, the sole occasion when the Seamuts technique was reproduced exactly, indicates that dilution is more rapid off Arish Mell than off Windscale.

A comparison of the results of the Windscale and the other Arish Mell experiments is not straightforward owing to the different techniques employed. Discharging at the sea bottom of the dye solution of specific gravity greater than sea water, as was done in Dorset, would retard dilution but a study of the parameters, A2 and γ (see section 12(a)) suggest that at least conditions are no worse for Dorset.

(k) A study of the analytical results for eight of the most successful days in Exercise Mermaid accounted for an average of about 150% of the actual dye discharged.

One amongst several possible explanations of this discrepancy is that the analytical figures obtained tended to err on the high side, due to the effect of particulate matter etc. on the Fluorimeter readings.

(l) Comparing the results obtained in Exercise Mermaid with those of Operation Seamuts and using the experience gained at Windscale with radioactive discharges, the following conclusions may be drawn:

If the pipeline is carried out to sea for a distance of two miles it would be safe to discharge 25,000 curies per month off Arish Mell. However, it is unlikely that an Authorisation for this figure would be granted in the first place.

Further restrictions would be placed on the discharge of alpha-emitters and on the contribution to the total amount made by ruthenium-106 and strontium-90.

25. Recommendations for future trials. It is considered that model experiments in a small canal would be a valuable means of studying diffusion by radioactive counting or colorimetric methods. In such tests the Reynolds number should be greater than 10^4 and thus, for a linear flow rate of 100 cm sec^{-1} the requirement is for a depth of 1 ft. and a width of 10 ft. A systematic study could then be made of the laws governing current distribution at the centre of the channel, the shape of the plume from a continuous discharge, the distance from the source at which vertical mixing is complete, the coefficients of longitudinal and lateral diffusion for a short discharge, the effect of roughening or curving the channel, and the most efficient method of terminating a pipe-line.

Experiments at sea with buoys should be given emphasis since they give very good information on the average drift due to tidal flow and are cheaper than dye experiments. Economical and accurate methods of tracking should also be investigated, and windage reduced as much as possible by means of drogues.

The experience of the present exercise suggests that continuous discharges should be predominant among dye experiments since they are easier to interpret and give information of more direct practical value.

It would be valuable to develop automatically-reading fluorimeters or absorptiometers to give a continuous record of dye concentrations as the ship is travelling, and to exploit the possibilities of photometric analysis of aerial photographs of the dye plume.

26. Acknowledgments. The authors gratefully acknowledge the help and co-operation of the Admiralty; the Commander-in-Chief, Portsmouth; the Hydrographer of the Admiralty; the Captain-in-Charge, Portland; the Queen's Harbour-master at Portland; the Commander-in-Chief of Lulworth Camp; the Director of Armament Supply; the Naval Armament Supply Officer at Bincleaves; Lt. Cmdr. A. S. Anderson, R.N., the Director of the National Institute of Oceanography; H.M. Underwater Development Establishment at Portland, and all the members of the U.K. Atomic Energy Authority who helped in this work.

TABLE III

ANALYSIS OF EDDY DIFFUSION PARAMETERS FOR EIGHT BEST MERMAID RUNS

Date	Release Point	Release Time B.S.T.	Remarks	Release Relative to H.M. Devonport	Drift at Release	Wind	State of Sea	H (metres)	A_1 (KM^2 3 hours)	A_2	γ (KM^2)	S_0 (KM)	α	N	L_0 metres	L_n metres	$\sqrt{\frac{L_0}{L_n}}$	H	λ_0	λ_n
17-9	O_3	08.37	Amino G only	2h 46m	6h W	E 4	M to R	28.5	1,000	800	830	+ 0.8	0.680	26	12.5	1.1	3.4	1.10	0.44	0.038
7-10	O_3	08.05	" " "	1h 17m	3h E	0	calm	28.5	1,000	600	1,100	- 0.75	0.90	16	50	0.4	11.2	1.76	1.75	0.014
12-10	O_3	08.28	" " "	-1h 57m	1h E	0	calm	28.5	900	600	225	- 0.5	0.18	16	180	5.5	5.7	2.54	6.30	0.192
22-10	O_3	10.20	" " + fluorescein mixture	1h 27m	1h E	SW 3	mod.	28.5	200	180	260	+ 0.5	0.21	22	19	1.6	3.4	0.51	0.67	0.056
28-10	O_4	10.18	" " "	-1h 34m	1h W	SW 4	M to R	28.5	700	500	860	- 1.1	0.705	50	5.1	2.5	1.4	1.10	0.18	0.087
29-10	O_3	11.32	" " (dilute solutions 3 cwt)	-1h 52m	6h E	SW 4-5	rough	28.5	1,000	700	190	0	0.155	25	111	3.5	5.6	1.34	3.9	0.123
5-11	O_4	10.13	" "	3h 17m	1½h E	W 3-4	M to R	28.5	1,500	1,300	770	- 1.2	0.63	19	67	1.8	6.1	3.04	2.3	0.063
9-11	O_3	07.30	1/3 ton fluorescein on surface, combined observations	-2h 25m	1h W	SW 6	rough	28.5	600	500	560	+ 1.2	0.46	24	12.5	3.3	1.9	1.29	0.43	0.115
			First run S = 0.7 KM) Using Combined Track Plot											(10	18.7	1.36	3.7	1.01	0.65	0.068
			Second " S = 1.7 KM)											(8	17.3	1.72	3.2	1.11	0.60	0.060
			Third " S = 3.6 KM)											(6	5.2	0.88	2.4	0.43	0.18	0.031
			First run S = 0.7 KM) Using Separate Track Plots											(10	3.7	1.9	1.4	0.53	0.13	0.066
			Second " S = 1.7 KM)											(8	5.8	2.5	1.5	0.76	0.20	0.088
			Third " S = 3.6 KM)											(6	7.0	1.4	2.2	0.35	0.25	0.060
12-11	O_3	07.30 to 10.30	Continuous discharge: from analysis of aerial photographs at 11.59, 12.08 and 12-13	-4h 20m to -1h 20m	E											1.0				0.035
17-11	O_3	10.30 to 13-10	Continuous discharge S = 0.8 KMS	+6h 00m to +9h 00m										44		0.575				0.013
16-11	O_3	13-10	300 Polythene envelopes after one hour	-3h 00m	Turning W to E	N	calm	28.5							0.745	0.11	2.2	-	0.026	0.0039
			Polythene envelopes after two hours.												0.97	0.32	1.75	-	0.034	0.0115

Table III (Continued)

Symbols

H is the depth of the sea at the release point.

A_1 is the average value of $C_{max}t$, where 10^9 C_{max} is the maximum measured relative concentration, regardless of depth, t hours after release, in gms per cc per ton released.

A_2 is the average value of $\bar{C}_{max}t$, where 10^9 C_{max} is the maximum depth-mean relative concentration (i.e. average at four depths).

γ and S_o are defined by $\bar{C}_{max} = \gamma/(S + S_o)$ where S is distance travelled in kms.

$L_s = \frac{1}{2} \langle \Delta X^2 \rangle / (S + S_o)$ is effective longitudinal diffusion coefficient/drift velocity.

$L_n = \frac{1}{2} \langle \Delta Y^2 \rangle / (S + S_o)$ is effective lateral diffusion coefficient/drift velocity.

$M = 4\pi H \gamma \sqrt{L_s L_n}$ = normalised quantity of dye, re-estimated from experimental data.

$\alpha = \gamma H^2$
$l_s = L_s/H$
$l_n = L_n/H$
} are dimensionless numbers.

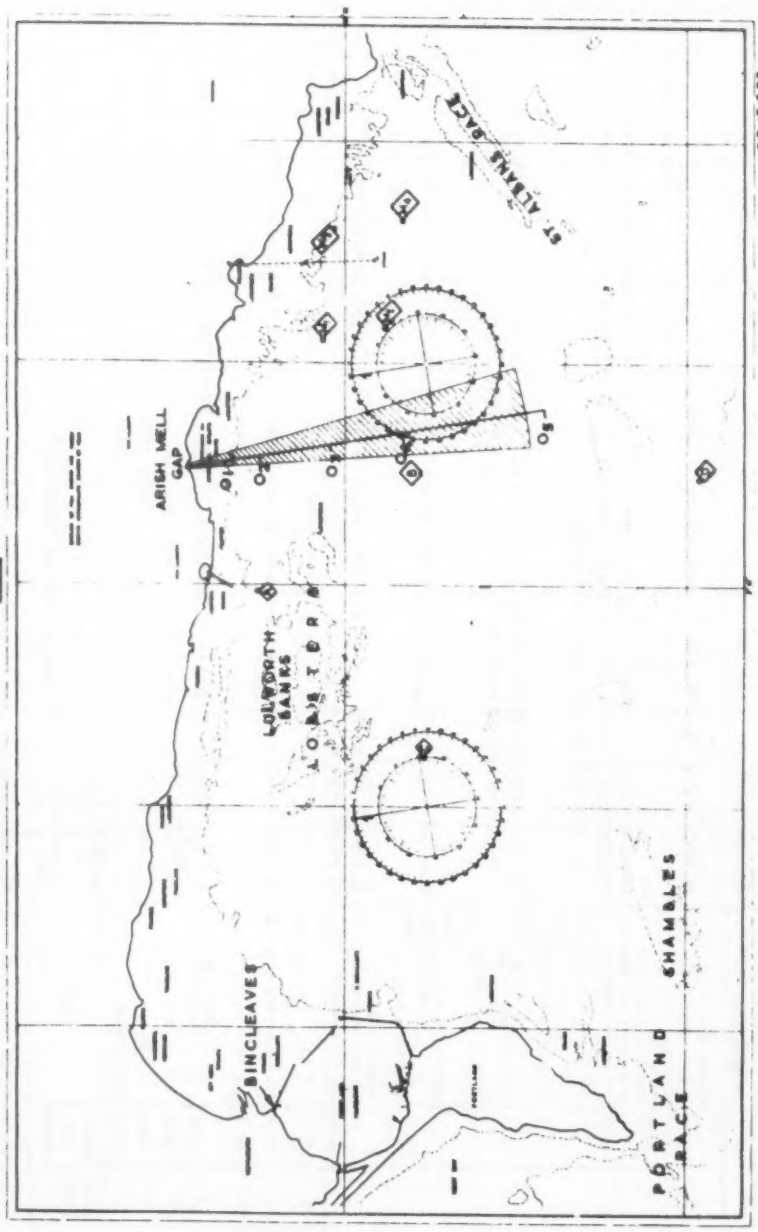

FIG. 1. REPRODUCTION OF ADMIRALTY CHART 2610 SHOWING PORTLAND–ST. ALBANS AREA. RR 15,252.
Reproduced from British Admiralty Chart 2610, with the permission of the Controller of H.M. Stationery Office, and of the Hydrographer of the Navy.

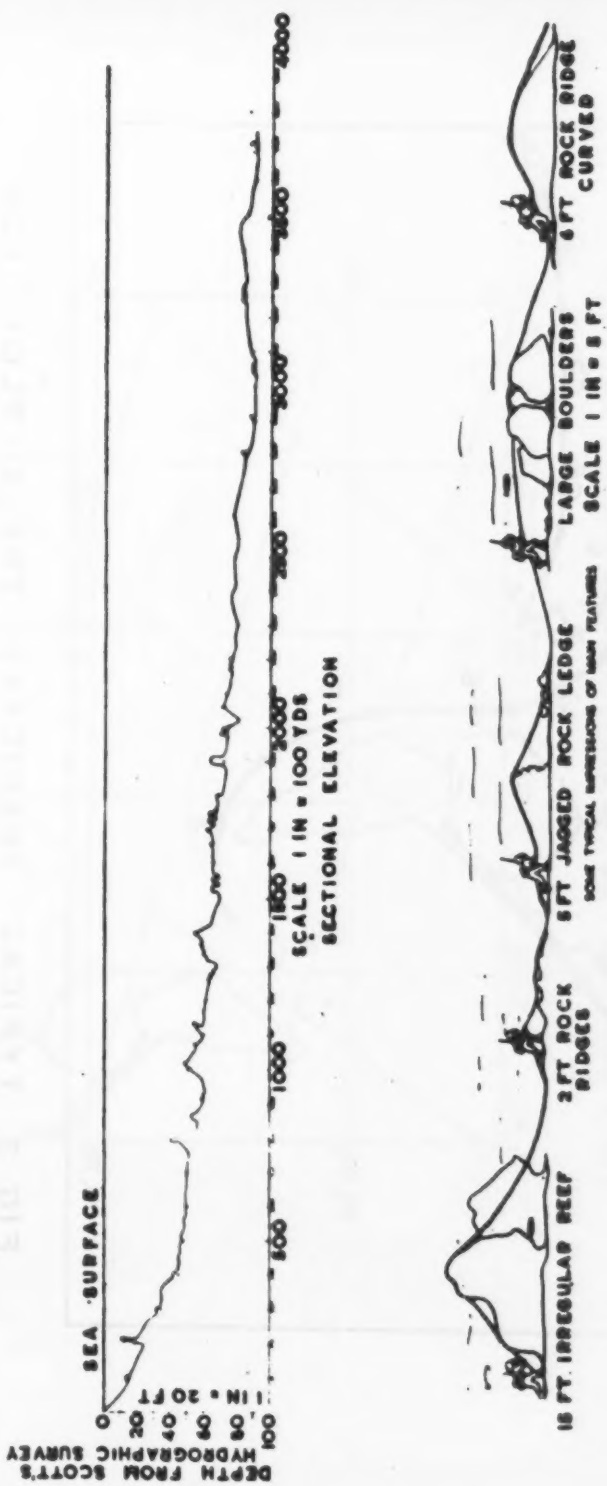
DEPTH FROM SCOTT'S HYDROGRAPHIC SURVEY
1 IN = 20 FT
SEA SURFACE
SCALE 1 IN = 100 YDS
SECTIONAL ELEVATION
18 FT. IRREGULAR REEF
2 FT ROCK RIDGES
6 FT JAGGED ROCK LEDGE
LARGE BOULDERS
SCALE 1 IN = 5 FT
6 FT ROCK RIDGE CURVED

FIG. 2. BOTTOM SURVEY OF WORMWOOD BAY
BY HMAUDE CLEARANCE DIVING TEAM, OCTOBER, 1955

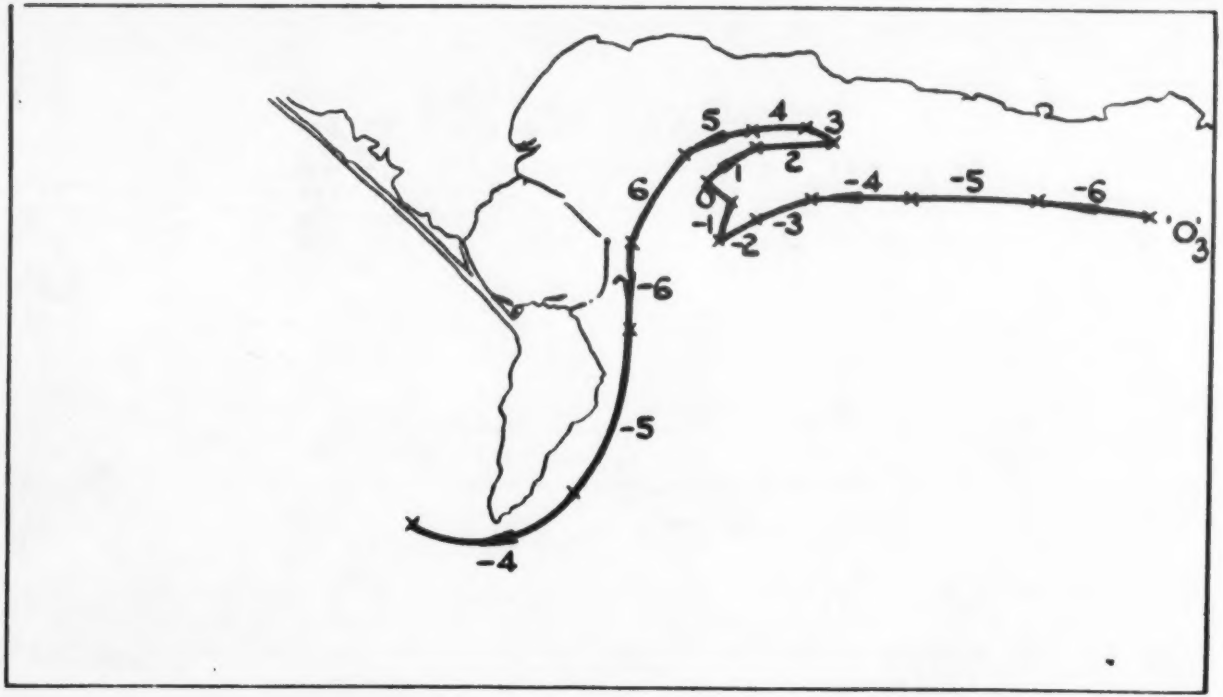

FIG. 3. TYPICAL PREDICTED TRACK PLOT FOR BOUY DRIFTING FROM O_3, STARTING SIX HOURS BEFORE HIGH WATER, DEVONPORT, SPRING TIDES.

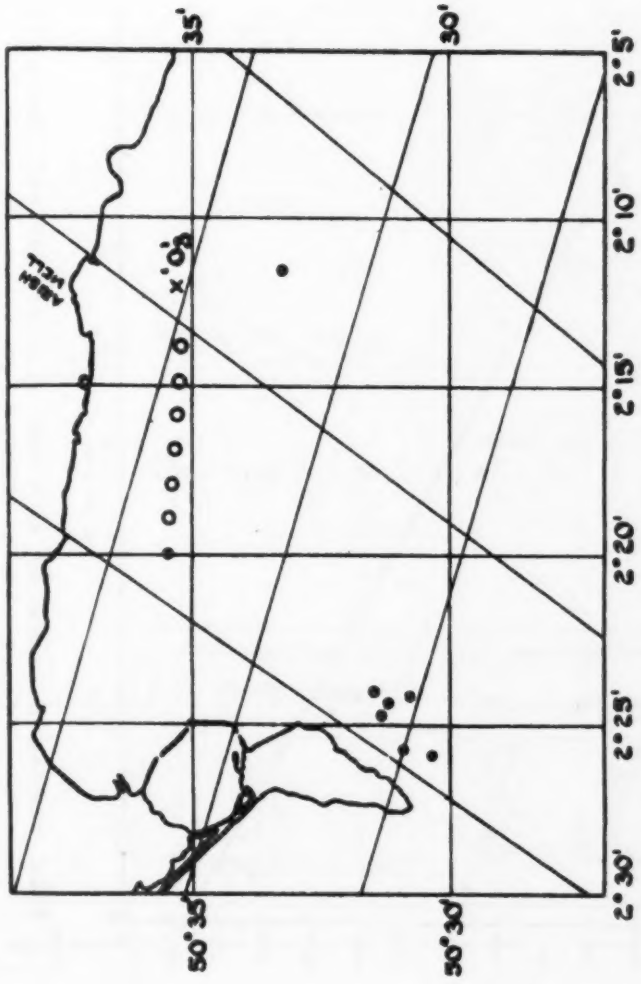

FIG. 4. RESULTS OF AERIAL AND SHIP SEARCH FOR PLASTIC ENVELOPES RELEASED BETWEEN 36 AND 21 HOURS PREVIOUSLY AT O_3.

• SEEN FROM AIRCRAFT o SEEN FROM SHIPS

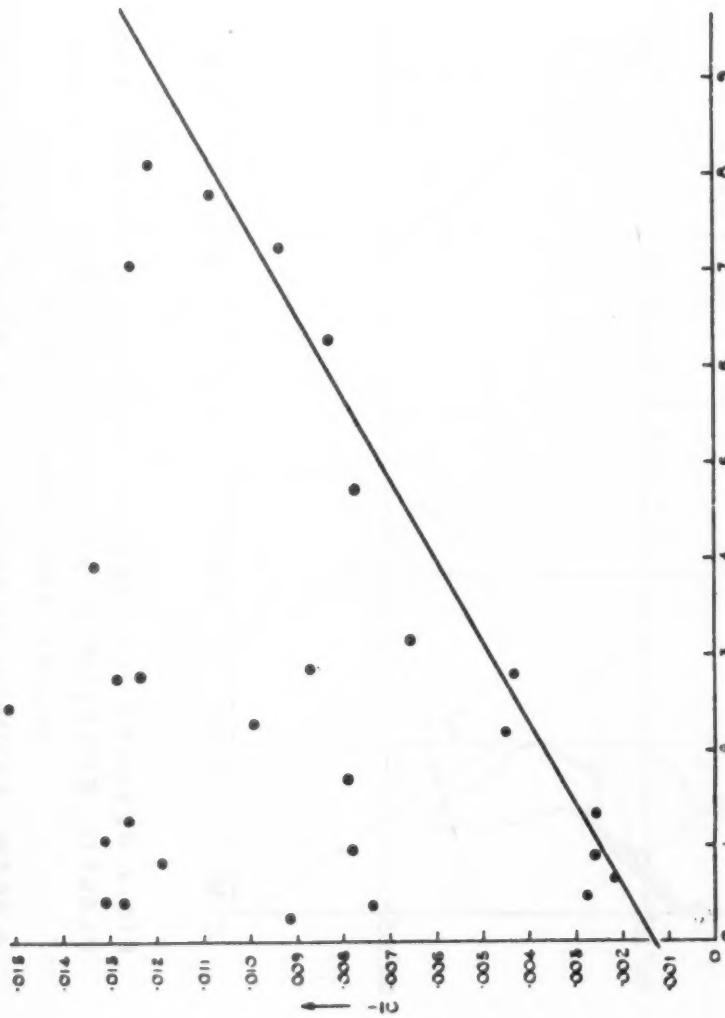

FIG.5. TYPICAL DIAGRAM OF DILUTION PLOTTED AGAINST DISTANCE TRAVELLED BY CENTRE OF PATCH.

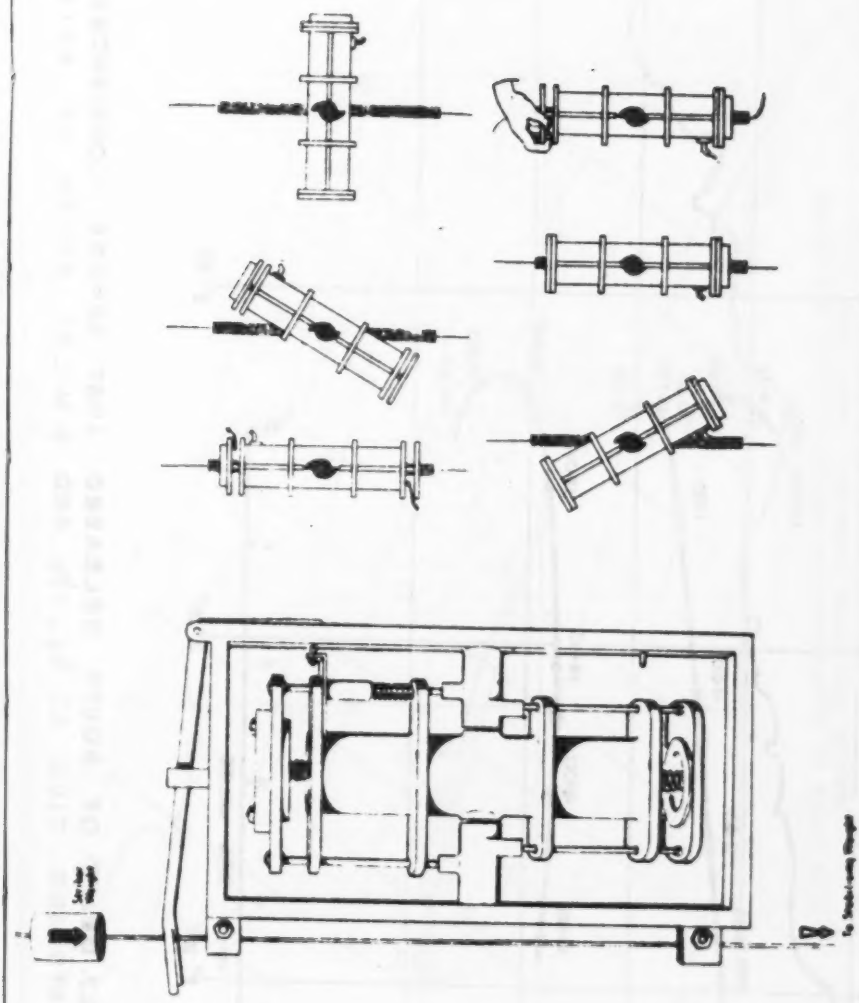

FIG. 6. A.E.R.E. MODIFICATION OF HANSEN-PETTERSEN SAMPLER

TRAVELLED BY CENTRE OF PATCH.

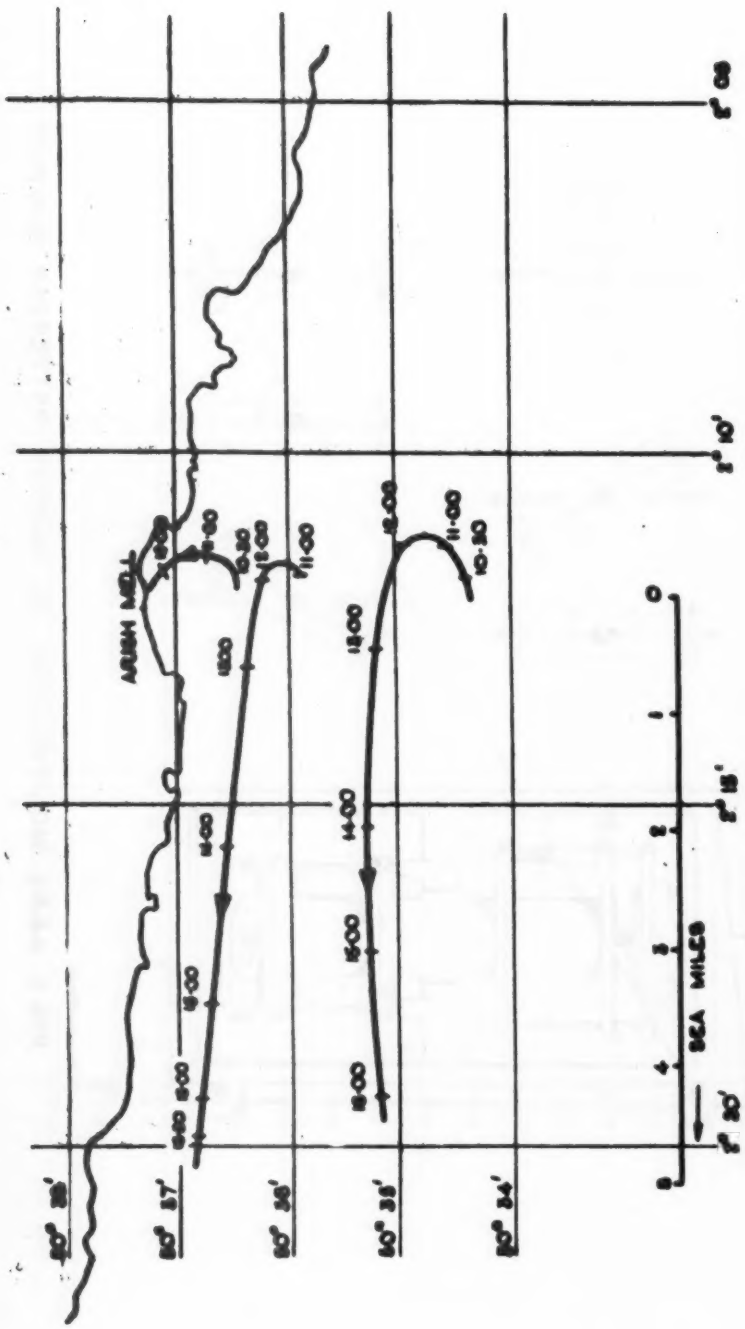

FIG.7. DRIFT OF BOUYS RELEASED JUST BEFORE COMMENCEMENT OF WESTGOING TIDE AT ¾, 1½ AND 3 MILES SOUTH OF ARISH MELL.

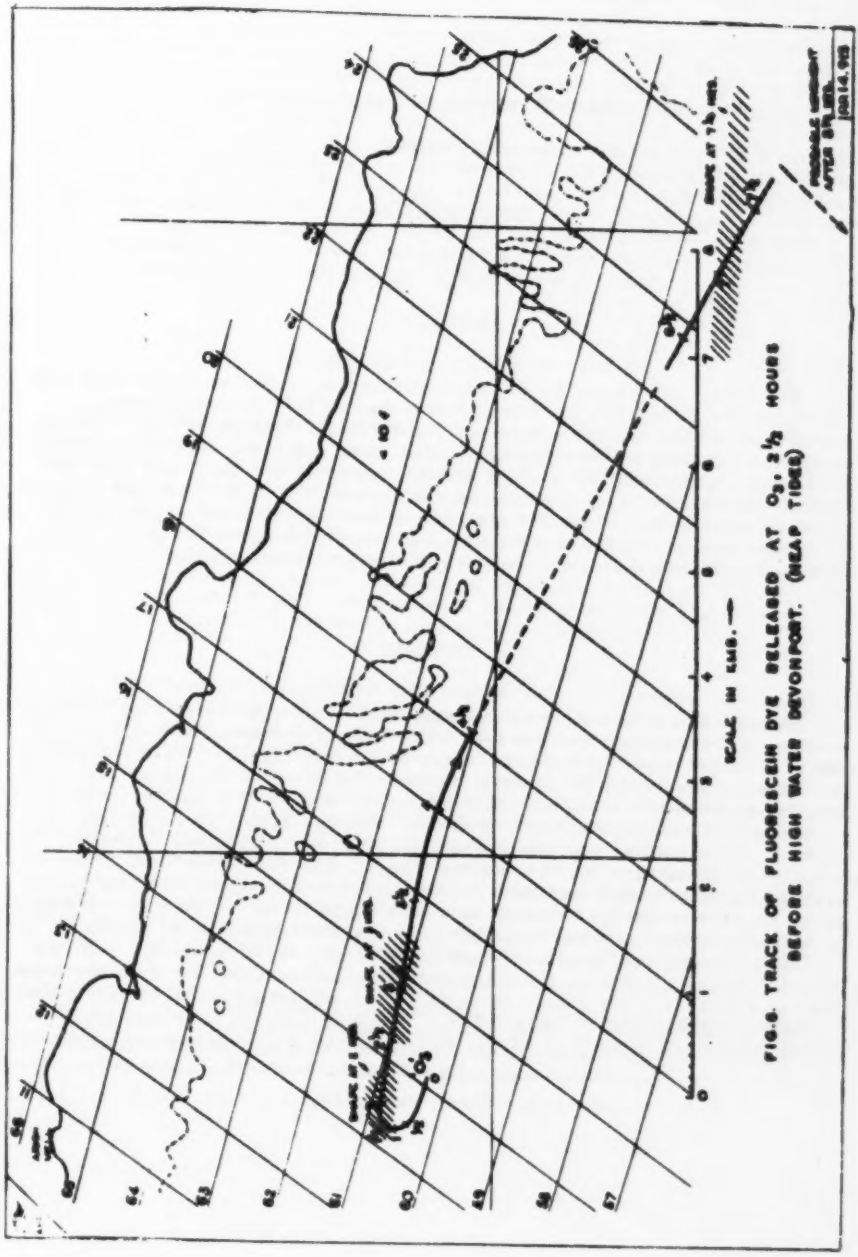

FIG. 6. TRACK OF FLUORESCEIN DYE RELEASED AT O_3, 2½ HOURS BEFORE HIGH WATER DEVONPORT. (NEAP TIDES)

WESTBOUND TIDE AT ¾, 1½ AND 3 MILES SOUTH OF ARISH MELL.

THE DISPOSAL OF RADIOACTIVE LIQUID WASTES INTO COASTAL WATERS

H. J. Dunster*

ABSTRACT

For about five years, experimental discharges of radioactivity have been made from the United Kingdom Atomic Energy Authority's Windscale Works, Sellafield, to the coastal waters off Cumberland. Samples of fish, seaweed, sea bed and shore sand have regularly been taken and their activity assessed. This report summarises the results of that programme and concludes that the maximum permissible discharge rate is not less than 20,000 curies per month of total beta activity. Specific limitations are necessary for strontium 90, for ruthenium 106 and for plutonium. Reference is made to the use of this information in estimating the safe discharges into other coastal waters.

1. INTRODUCTION

Many of the processes and laboratory operations associated with a nuclear power programme produce radioactive liquid wastes, which may be dealt with by any of a large number of variants of two basic procedures. These procedures are storage, preferably in a highly concentrated form, or dispersal into the natural environment. The main fission product wastes of a nuclear power programme are of such high activity that only storage, either in controlled conditions, or in natural regions of isolation, can be considered. However, in addition to these high activity wastes, there arise substantial quantities of wastes in which the radioactivity is very dilute. Treatment of these wastes so as to concentrate the activity in a form suitable for storage is not always an economic proposition and dispersal into the environment under carefully controlled conditions is often a more satisfactory way of disposal. In the United Kingdom, hospitals, factories and laboratories which use radio-isotopes discharge much of their liquid waste to sewers and rivers under control enforced by existing public health legislation. The only large scale disposals of radioactivity are those made by the United Kingdom Atomic Energy Authority and

* United Kingdom Atomic Energy Authority, Industrial Group

special legislation has been devised to control these disposals. Under this legislation, the Atomic Energy Authority is permitted to dispose of radioactive waste only in accordance with specific authorisations issued by two Departments of Her Majesty's Government. These Departments appoint inspectors who have right of access to the Atomic Energy Authority's premises to satisfy themselves that the authorisations are being complied with. Only one series of discharges under these authorisations is on a substantial scale and this is the discharge of aqueous waste to the sea from Windscale Works at Sellafield in Cumberland. Windscale Works contains reactors, chemical plants, and laboratories concerned both with plant control and with the technology of nuclear power and the wastes, therefore, contain primarily fission products and nuclear fuels such as plutonium. They consist of dilute aqueous solutions, which are neutralised immediately prior to discharge, and the radioactivity is thus not necessarily present in genuine solution, but may be in the form of a very dilute suspension. The wastes are discharged to sea through a pipe line extending about three kilometres beyond the high water mark.

2. THE PRELIMINARY STUDIES AT WINDSCALE

When the design of Windscale Works was first being considered, it was recognised that it might be convenient to discharge a few hundred curies per month in the form of liquid waste, and the choice of a coastal site greatly simplified the disposal problems. Discharges of radioactivity of this magnitude cannot be considered, even into the sea, without a detailed preliminary investigation and review of the possible problems. Approximate numerical assessment of these problems is possible and will normally indicate that some of them are predominant while others can be dismissed as insignificant. The relative importance of these problems will depend greatly on the details of the local marine environment and on the extent to which marine resources are exploited for man's use.

At Windscale the preliminary work started with hydrographic studies of the diffusion processes and the tidal streams. The diffusion studies were undertaken by releasing large quantities of dye at various points off the coast and sampling the resultant patch from ships during the following few hours. From the rate of spread of the dye and from its rate of dilution it was possible to estimate diffusion coefficients and ultimately to decide on the length of pipeline required to avoid high concentrations on the shore. This work was reported at the 1955 Geneva Conference by Seligman[1]. Tidal stream studies were made using current meters and drift markers and showed that although there was considerable tidal movement in the area there was little or no residual current. This conclusion was subsequently confirmed by studies of the distribution of salinity in the north-east Irish Sea. These studies showed that the removal of fresh water running off the land was predominantly by eddy

(1) SELIGMAN, H. The discharge of radioactive waste products into the Irish Sea. Part I. First experiments for the study of movement and dilution of released dye in the sea. International Conference on Peaceful Uses of Atomic Energy, Volume 9, Paper P.418. Geneva (1955).

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diffusion rather than by currents. There was, of course, considerable movement of surface water as the result of winds. This movement did not greatly affect the bulk transfer of water, but it did contribute considerably to the turbulence.

The preliminary assessments showed only three main potential dangers. These were radioactivity in edible fish and in edible seaweed and radiation from the shore. Other risks, such as irradiation of bathers, ingestion of sand or sea water and the use of seaweed as a fertiliser, were shown to be of a lower order of importance. The work was, therefore, concentrated on estimates of the probable relationship of the activity of fish, seaweed and sea shore with the activity of the sea water. Programmes of work were started on the distribution and commercial capture of edible fish from the region of the proposed pipeline and on the distribution of edible seaweed along that part of the Cumberland coast. The study of fish movement involved the capture and marking of over 35,000 fish in the pipeline region. Some of these fish were recaptured in a planned fishing programme while others were returned through commercial channels. Nearly half the marked fish were subsequently recaptured. The results showed that the fish made small seasonal movements, probably governed mainly by temperature changes, and that when they left the area very few of them travelled further than the limits of the North Irish Sea. The proportion of marks in the commercial landings indicated that there would be a considerable dilution by fish from areas remote from Windscale. The studies of seaweed suggested that no great dilution with inactive weed could be relied upon since the Cumberland weed was harvested only over about 40 kilometres of the shore line and all of it was sent to one area in South Wales, where it formed a considerable fraction of the total supply. These environmental studies were supported by laboratory work in which fish and seaweed were kept in tanks of sea water to which radioactive materials had been added. Regular sacrificing of the fish and sampling of the seaweed enabled estimates to be made of the concentration factor between sea water and the edible materials. Measurements were also made of the concentration in fish and seaweed of inactive elements which were expected to appear in active forms in the effluent. A comparison of these concentrations with the natural concentrations of the elements in sea water enabled a further estimate to be made of the maximum concentration factors which could be expected.

The results of these preliminary studies showed that the effluent would leave the pipeline and would be rapidly mixed with large volumes of the sea water which, off this part of the coast, undergoes complete vertical mixing. The diluted radioactivity would then be carried up and down the coast by the tidal stream and would slowly diffuse into the whole of the northern Irish Sea and would finally pass out into the Atlantic Ocean. Only in the area within a few kilometres of the outlet would the activity concentration be significantly different from the natural background activity of sea water. The coastal water off Cumberland is heavily loaded with suspended solids including sand, mud and organic detritus. During the process of dilution much of the radioactivity would become adsorbed onto this suspended matter and onto the sea bed and to a lesser extent onto the sea shore and seaweed. The fish which live off this part of the Cumberland coast are those which live on the sea bed and of these plaice, Pleuronectes platessa, are the most important. These fish would take up activity, partly from the water, partly from the solid particles amongst which they live, and partly from their food, which consists mainly of inverte-

brates living on the sea bed. These various concentration processes were expected to cause the activity of sand, seaweed and fish to reach ten or a hundred times, or exceptionally perhaps a thousand times, the activity concentration in the sea water. No precise predictions were possible because it was impracticable to reproduce the natural conditions on a laboratory scale.

By combining these forecasts with estimates of the maximum permissible activity levels in fish and seaweed and on the shore, it was possible to assess the maximum permissible discharge rate. A deliberate factor of safety of ten was introduced into the calculations because of the uncertainty of some of the predictions. From this work, which was reported at Geneva in 1955 by Dunster[2], it was concluded that a discharge of about 100 curies per day of beta activity and of about 0.1 curie per day of alpha activity would be completely safe.

3. THE STUDIES ON DISCHARGED RADIOACTIVITY

The preliminary studies had included no discharges of radioactivity because it was recognised that such discharges were unlikely to produce useful experimental results unless they were continued for a period of some months. However, by 1952 it was possible to make such regular discharges from Windscale and it was decided to combine these with a detailed monitoring programme to form a planned experiment. This experiment, whose aim was not only to show the safety of the discharges, but also to establish the values for the maximum permissible discharges, was supported by the Ministries responsible for issuing the authorisations for waste disposal. Since that time, the discharges have been deliberately maintained at a level, below the authorised rate, but high enough to obtain detectable activity levels in samples of fish, seaweed and shore sand and the experiment is still proceeding.

3.1. THE MONITORING PROGRAMME

The main monitoring effort during the period since 1952 has been concentrated on measuring the activity of fish, seaweed, shore sand and sea bed. A few attempts have been made to estimate the activity of the sea water but the presence of finely divided solid matter in suspension makes the interpretation of such results very difficult. The aim of the monitoring programme has, therefore, been directly to relate the activity in the materials with which man comes in contact to the rate of discharge of radioactivity. It has not, therefore, been possible to compare the results of the monitoring programme step by step with the results of the preliminary studies. The shore sand samples

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(2) DUNSTER, H. J. The discharge of radioactive waste products into the Irish Sea. Part 2. The preliminary estimate of the safe daily discharge of radioactive effluent. Paper P.419. Geneva (1955)

have been assessed for total beta activity since only the beta, and to a lesser extent the gamma, radiations from the shore are of importance. Sea bed samples have also been assessed, partly because the sea bed may contaminate fishing gear, but also because the distribution of activity reflects the dispersal of the active effluent in the sea water. Both fish and seaweed are used for food and, because of the wide range of toxicities between such materials as plutonium, strontium and other fission products, analytical methods have been used to make separate estimations of plutonium, strontium, ruthenium and total beta activity. The total number of determinations involved in this monitoring programme has increased from about 250 per year to about 1,000 per year. In addition to these environmental measurements, samples have been taken from the outgoing effluent. A sample of each discharge has been assessed for total beta activity for plant control purposes and a representative sample has been bulked and given a detailed analysis every month.

3.2. THE MAXIMUM PERMISSIBLE LEVEL OF ACTIVITY IN MARINE MATERIALS

The permissible activity level in the marine materials sampled depends both on the isotope concerned and on the part the material plays in man's life. The basic standards which have been used in the studies at Windscale Works are those recommended by the International Commission on Radiological Protection, in particular those recommendations published after the meeting in 1953,(3). The figures given by the International Commission relate primarily to the exposure of radiation workers, who are under medical supervision, and these figures have been reduced by a factor of ten before applying them to members of the general public.

In estimating the permissible activity of the shore sand, it has been assumed that no-one regularly spends more than 100 hours per year on the sands and that a dose of 1.5 rads per year is a permissible annual dose for the mixture of beta and gamma radiation involved. The samples have been assessed by beta counting on a thick source and the results have been calibrated in terms of the concentration of potassium 40 which would give the same counting rate. The permissible level adopted for shore samples assessed in this way was 2.5×10^{-2} microcuries per gramme dry weight which, for a deep and extended layer of contaminated sand, represents a dose of slightly less than 1.5 rads in 100 hours. The use of the dry weight of the sample introduces a small safety factor. Since most of the dose will be delivered by beta radiation, the figure of 1.5 rads per year also contains a small safety factor. Neither of these factors has yet been taken into account. The samples have been taken at points up to a distance of a few kilometres from the point nearest the outlet, but the distribution of samples has been weighted by more frequent sampling near the outlet. In calm weather, a fine black silt settles out on parts of the sand and remains until it is removed by heavier seas. The deposits are localised and shallow and the radiation dose they deliver will not be likely

(3) International Commission on Radiological Protection, Recommendations, revised December 1st, 1954. British Journal of Radiology, Supplement No. 6, (1955)

to exceed the figure of 1.5 rads per year provided the activity level remains below about 1×10^{-1} microcuries per gramme. Radioactivity on the sea bed is no direct danger to man but because of the possible contamination of fishing gear a limit of 1×10^{-1} microcuries per gramme has again been set. This value has been based on experimental measurements of radiation levels from fishing gear used near the effluent outlet. The sea bed samples have been taken within a few kilometres of the outlet mainly within the narrow band parallel to the coast where most of the activity if deposited.

The permissible activity of fish depends on the consumption of locally landed fish, not all of which is caught in the vicinity of the effluent outlet. However, because of the very low activity levels, it has not been feasible to monitor these fish directly and the fish samples have, therefore, been obtained by trawling in the area within a few kilometres of the outlet. A few people in Cumberland eat an average of about 250 grammes per day of local fish, but as only a small proportion of this comes from the area near the outlet, the maximum permissible level in the fish samples has been based on a daily consumption of 25 grammes. The international recommendations for the maximum permissible concentrations in drinking water assume a daily consumption of 2,200 grammes of water and the maximum permissible concentration in fish samples has, therefore, been set at 100 times the permissible level for water consumed by members of the general public, that is, at ten times the maximum permissible level for water consumed by radiation workers.

A similar assessment has been made of the consumption of seaweed and it has been found that a few people eat an average of as much as 75 grammes per day. No allowance has yet been made for dilution by seaweed from areas remote from Windscale and the sampling programme has been used to obtain an estimate of the average activity of seaweed from the whole Cumberland coast. The maximum permissible concentrations in seaweed are, therefore, set at 3.3 times the corresponding maximum permissible concentrations in drinking water for consumption by radiation workers. Disregarding the dilution by inactive weed introduces a safety factor which is unlikely to be less than two.

While these estimates of the maximum permissible activity of fish and seaweed are adequate for specific isotopes, measured by specific chemical methods, they need further consideration for samples assessed for total beta activity. Such samples are counted as thick sources and the results are thus dependent on the beta energy of the contaminant. Potassium 40 is again used as a standard. Much of the activity has been contributed by ruthenium 106 and part of the remainder is due to cerium 144. Both these isotopes have maximum permissible concentrations in drinking water of 1×10^{-4} microcuries per millilitre but both have beta energies in the region of 3 MeV and are overestimated in the thick source by a factor of about two. Other contributing isotopes will not be overestimated but have maximum permissible concentrations of 2×10^{-4} microcuries per millilitre or more. The permissible activities of fish and seaweed have, therefore, been based on this value of 2×10^{-4} microcuries per millilitre in drinking water, although it involves a small safety factor because of the presence of less toxic isotopes.

Since ruthenium 106 is a major constituent of the discharges, it is more satisfactory to treat this isotope separately, rather than to associate it with

the rest of the beta emitters. Many of the fish and seaweed samples have, therefore, been assessed for ruthenium 106 as well as for total beta activity. In these cases there is no difficulty in assigning a value for the maximum permissible activity due to ruthenium, but a difficulty arises in defining both the activity level and the maximum permissible activity due to beta emitters other than ruthenium 106. The expedient adopted in this work has been to estimate total beta activity by counting a thick source, with potassium 40 used as a standard, and to subtract from it the value which the ruthenium 106 would have given if it had been assessed in the same way and not by chemical separation and counting as a thin source. The difference value obtained in this way is referred to as the total activity excluding ruthenium 106, and the maximum permissible level which is applied to it is that derived from a value of 2×10^{-4} microcuries per millilitre in drinking water.

This procedure has two disadvantages. In the first place, the factor used to convert ruthenium activity to its equivalent thick source value depends on the exact nature of the fish or seaweed ash and is thus variable. In cases where the activity in the sample is largely due to ruthenium this variation causes a very large uncertainty in the figure for total beta activity excluding ruthenium 106. The second disadvantage is due to the fact that most of the beta emitters in the unidentified group have higher maximum permissible levels in water than 2×10^{-4} microcuries per millilitre, and an appreciable but unknown safety factor is thus introduced. These disadvantages can be avoided only by carrying out an extensive radiochemical analysis of the samples. It is hoped in future work to obtain averages by bulking samples rather than by averaging results and in this way to reduce the number of samples for analysis to the point where detailed radiochemical analysis becomes feasible.

The maximum permissible levels adopted at Windscale are summarised in Table 1.

TABLE 1

MAXIMUM PERMISSIBLE LEVELS OF ACTIVITY IN MARINE MATERIALS

Type of Activity	m.p.l. in water (μc/ml)	Marine Material	m.p.l. in material (μμc/g)
Total beta	-	Shore sand Shore silt Sea bed	25,000 100,000 100,000
Total alpha (assumed to be Pu^{239})	3×10^{-6}	Fish Seaweed	30 10
Total beta (including or excluding Ru^{106})	2×10^{-4}	Fish Seaweed	2,000 670
Ruthenium 106	1×10^{-4}	Fish Seaweed	1,000 330
Strontium 90	8×10^{-7}	Fish Seaweed	8 2.7

3.3. THE RESULTS OF THE MONITORING PROGRAMME

At intervals during the period since the beginning of discharges, reviews have been made of the implications of the results and the work has, therefore, been divided into a series of somewhat arbitrary experimental periods. In presenting the results it has been found convenient to retain this division into experimental periods.

The first period, covering the year 1952 and the first quarter of 1953, was used to assess the spread of radioactivity in the marine environment and to find out how soon an equilibrium would be reached. The results showed that equilibrium conditions were achieved after discharges lasting for only a few months and this has been confirmed by the later experience. This short time can be explained by presuming a fairly rapid transfer of activity out of the immediate environment. It is of considerable interest that this process affects activity on the sea bed as well as that in seaweed and fish.

The subsequent periods, numbered 2 to 6, range from nine to fifteen months and cover the period up to the end of 1957. A preliminary report on the results of period 2, up to April 1954, was made by Fair and McLean[4] at the 1955 Geneva Conference, and these results were used as the basis for a complete re-assessment of the permissible discharges. This re-assessment showed that discharges of nearly 1000 curies per day of beta activity and of a few curies per day of alpha activity would be safe provided that additional restrictions were put on the discharges of ruthenium 106 and strontium 90. Periods 3 and 4 were used to confirm these conclusions and in 1956 the rate of discharge of radioactivity was deliberately increased, partly to dispose of unwanted wastes, but principally to yield better experimental data. These results have not made it necessary to modify the maximum permissible discharges adopted at the 1954 assessment.

Table 2 shows the details of the experimental periods and the amounts of the various materials discharged. This is followed by Tables 3 to 7, which show the numbers of samples analysed and the arithmetic mean of the results in each period. These tables show that the levels of ruthenium and total beta activity in seaweed, the limiting factors in these discharges, have been systematically below the maximum permissible levels. In all other cases, the activity levels in marine materials have been below about 10 percent of the maximum permissible levels.

In addition to the main sampling programme, occasional surveys have been made at distances extending up to about 50 kilometres from the outlet. At this distance the activity levels do not differ significantly from the natural background levels.

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(4) FAIR, D. R. and McLEAN, A. S. The discharge of radioactive waste products into the Irish Sea. Part 3. The experimental discharge of radioactive effluents. Paper P.420. Geneva (1955).

TABLE 2

EXPERIMENTAL PERIODS AND AMOUNTS DISCHARGED

Period Number	2	3	4	5	6
Dates	6/4/53 25/4/54	25/4/54 25/6/55	26/6/55 4/3/56	4/3/56 31/3/57	31/3/57 5/1/58
Duration (Months of 28 days)	14	15	9	14	10
Mean Discharges (curies/28 days)					
Total alpha	1.25	1.53	12.33	4.89	4.61
Total beta	1350	2011	1326	6572	4549
Ruthenium 106	364	709	247	3280	1483
Total beta excluding Ru^{106}	986	1302	1079	3292	3066
Strontium 90	74	33	27	147	143

TABLE 3

RADIOACTIVITY OF SHORE SAND

Type of activity	Period	Number of samples	Mean activity (μμc/g dry weight)	m.p.l. (μμc/g dry weight)
Total beta	2	40	24	
	3	38	24	
	4	30	36	25,000
	5	46	74	
	6	25	57	

TABLE 4

RADIOACTIVITY OF SHORE SILT

Type of activity	Period	Number of samples	Mean activity (μμc/g dry weight)	m.p.l. (μμc/g dry weight)
Total beta	2	5	5,880	
	3	9	3,510	
	4	4	4,080	100,000
	5	50	11,980	
	6	33	5,930	

TABLE 5

RADIOACTIVITY OF SEA BED

Type of activity	Period	Number of samples	Mean activity (μμc/g dry weight)	m.p.l. (μμc/g dry weight)
Total beta	2	103	1,260	
	3	195	580	
	4	113	690	100,000
	5	249	4,030	
	6	64	4,790	
Ruthenium 106	5	88	2,525	100,000
	6	24	4,249	

TABLE 6

RADIOACTIVITY IN FILLETS OF PLAICE

(PLEURONECTES PLATESSA)

Type of activity	Period	Number of samples	Mean activity (μμc/g wet weight)	m.p.l. (μμc/g wet weight)
Total alpha	3	26	0.020	
	4	28	0.008	
	5	42	0.012	30
	6	13	0.048	
Total beta	3	26	3.6	
	4	28	4.2	
	5	42	9.1	2,000
	6	13	7.0	
Ruthenium 106	3	26	0.80	
	4	29	0.71	
	5	42	2.35	1,000
	6	11	2.25	
Total beta excluding Ruthenium 106	3	26	2.0	
	4	28	2.8	2,000
	5	42	4.4	
	6	11	2.5	
Strontium 90 (a) (b)	3	26	0.06	
	4	29	0.05	8
	5	42	0.05	
	6	11	0.06	

NOTES (a) All these results are close to the threshold of detection.

(b) All the results for strontium 90 include a small contribution from strontium 89.

TABLE 7

RADIOACTIVITY IN EDIBLE SEAWEED

(PORPHYRA UMBILICALIS)

Type of activity	Period	Number of samples	Mean activity (μμc/g wet weight)	m.p.l. (μμc/g wet weight)
Total alpha	2	36	0.11	
	3	117	0.14	
	4	45	0.33	10
	5	257	0.27	
	6	131	0.22	
Total beta	2	40	92	
	3	145	96	
	4	91	96	670
	5	256	260	
	6	130	226	
Ruthenium 106	2	55	22	
	3	68	44	
	4	33	40	330
	5	162	120	
	6	52	181	
Total beta excluding ruthenium 106	2	40	48	
	3	62	22	
	4	33	40	670
	5	159	60	
	6	-	- (a)	
Strontium 90 (b)	2	17	0.23	
	3	48	0.03	
	4	36	0.07	2.7
	5	57	0.21	
	6	9	0.04	

NOTE: (a) The uncertainty in interpretation of the results for this period is too great to allow them to be used. (See para. 16)

(b) All the results for strontium 90 include a small contribution from strontium 89.

The aim of the sampling programme has not been solely to demonstrate the safety of the discharges, although that has been a necessary part of the operation. Equally important has been the estimate of the maximum amount of radioactivity which can be discharged with complete safety into the coastal waters off Cumberland. This estimate has been made by taking a weighted mean of the results from each period for the levels of the various activities in seaweed, the limiting material. This weighted mean has then been divided by the overall mean rate of discharge to give the activity level expected from a discharge rate of one curie per 28 days. When this number is divided into the appropriate maximum permissible level, the estimated maximum permissible rate of discharge is obtained. This process is shown in Table 8. The only weighting factor used has been the length of the period. The ease, and probably the accuracy of the analyses increases as the rate of discharge of activity increases, but the general uncertainties in sampling procedures in this type of work outweigh any such increase and it was not felt that it would be justified to give any weight to the discharge rate. One sampling error is known to exist and is caused by a preponderance of seaweed samples from the region of the coast near to the discharge point. A correction factor of 1.5 has been used to reduce this error and is incorporated into the final estimate of the activity resulting from a discharge rate of one curie per 28 days. To simplify the comparison between periods, Table 8 also includes the values of the mean activity resulting from a discharge rate of one curie per 28 days for each period separately. These values have not been adjusted by the factor of 1.5.

TABLE 8

WEIGHTED MEAN ACTIVITIES IN SEAWEED FOR A UNIT DISCHARGE RATE AND MAXIMUM PERMISSIBLE DISCHARGES

Type of activity	Period	Mean activity for a discharge rate of 1 curie/28 days (μμc/g)	m.p.l. in seaweed and associated maximum permissible discharge rate
Total alpha	2 3 4 5 6	8.8×10^{-2} 9.2×10^{-2} 2.7×10^{-2} 5.5×10^{-2} 4.8×10^{-2}	10 μμc/g
Weighted mean(a)	All periods	3.1×10^{-2}	320 c/28 days
Total beta	2 3 4 5 6	6.8×10^{-2} 4.8×10^{-2} 7.2×10^{-2} 4.0×10^{-2} 5.0×10^{-2}	670 μμc/g
Weighted mean(a)	All periods	3.2×10^{-2}	21,000 c/28 days
Ruthenium 106	2 3 4 5 6	6.0×10^{-2} 6.2×10^{-2} 16.2×10^{-2} 3.7×10^{-2} 12.2×10^{-2}	330 μμc/g
Weighted mean(a)	All periods	4.1×10^{-2}	8,000 c/28 days
Total beta excluding Ru^{106}	2 3 4 5 6	4.9×10^{-2} 1.7×10^{-2} 3.7×10^{-2} 1.8×10^{-2} -	670 μμc/g
Weighted mean(a)	All periods	1.7×10^{-2}	39,000 c/28 days
Strontium 90	2 3 4 5 6	31.1×10^{-4} 9.1×10^{-4} 25.9×10^{-4} 14.3×10^{-4} 2.8×10^{-4}	2.7 μμc/g
Weighted mean(a)	All periods	9.7×10^{-4}	2,800 c/28 days

Note: (a) Adjusted for non-uniform distribution of sampling. (see page 1409)

The figures shown in Table 8 for the maximum permissible discharges are the best that can be made at present, but they cannot yet be regarded as final. In any case they cannot be applied in practice without consideration of possible additive effects of concurrent discharges of different isotopes. In particular, strontium and the alpha emitters are bone seekers and must be regarded as additive, while both ruthenium and the majority of the other beta emitters have to be limited because of the dose they deliver to the lower part of the gastro-intestinal tract and must, therefore, be treated as another additive group. The difficulties of assessing both the magnitude and the maximum permissible levels of total beta activity necessitate the inclusion of safety factors which cannot yet be properly evaluated. These factors, combined with the effect of dilution of the Cumberland seaweed by weed supplied from other areas, mean that the maximum permissible discharges have been underestimated by a factor which is unlikely to be less than three.

4. RADIOACTIVE DISCHARGES IN OTHER COASTAL WATERS

The work reported here has been entirely concerned with studies of the discharges off the Cumberland coast, but it can, in part, be applied to problems in other coastal areas. The limiting factors in coastal disposal will usually be local peculiarities and it is, therefore, helpful to summarise the peculiarities of the coastal environments of Windscale.

No regular currents, but a good tidal stream parallel to the coast.

Considerable turbulence, giving good vertical mixing and dispersion by eddy diffusion.

Considerable suspension of fine particles.

No shell fish used for human food.

Local fish are bottom feeders, remaining for some time in the local area, but not completely static.

Edible seaweed commercially harvested on the shore.

Sands used by holiday-makers.

Apart from the edible seaweed and the lack of any regular currents, most of these features tend to encourage the good dispersal of radioactivity and to reduce its reconcentration in materials which are of interest to man.

In assessing the disposal problems at any site in relation to the experience gained at Windscale it is convenient to start from the effects of a unit discharge of one curie per month (28 days) from Windscale. Table 9 shows the weighted mean results obtained from the earlier tables, with the addition of the mean results of some 70 analyses of the flesh of mussels, Mytilus sp., from a few kilometres from the Windscale discharge point. The table also shows the

relevant maximum permissible activity levels and the fraction of these permissible levels that results from a continued discharge of one curie per month. With appropriate local adjustments to the values in columns 2 and 3, Table 9 can be used to make a preliminary estimate of the safe discharge rate into other coastal environments. The accuracy of such estimates will depend very much on the degree of similarity of the environment to that at Windscale and on the extent to which it proves possible to make quantitative comparisons of such variables as the degree of dispersion, the uptake by different species of fish and seaweed, and man's use and consumption of marine products.

In addition to the Cumberland coast two other areas in the United Kingdom have been the subject of investigations aimed at assessing their suitability for radioactive waste disposal. These have been the North coast of Scotland, near Thurso, where the Dounreay Experimental Reactor Establishment is sited, and the South coast of England, near Weymouth, which is close to the new research establishment at Winfrith Heath. At both these sites lobsters are of commercial importance but they are otherwise completely different. The coast near Dounreay is rocky and the water is generally clear apart from the presence of finely ground shells in suspension near the shore. The shore in Weymouth bay is sandy and the water consequently carries a heavy suspension of particles.

TABLE 9

SUMMARY OF RESULTS OF DISCHARGES FROM

WINDSCALE

Type of activity and of sample	Weighted mean activity for a discharge rate of 1 curie/28 days (μμc/g)	m.p.l. (μμc/g)	Fraction of m.p.l. resulting from a discharge rate of 1 curie/28 days
Total alpha			
Seaweed	3.1×10^{-2}	10	3.1×10^{-3}
Fish	4.1×10^{-3}	30	1.4×10^{-4}
Mussels	3.1×10^{-1}	30 (a)	1.0×10^{-2}
Total beta			
Seaweed	3.2×10^{-2}	670	4.8×10^{-5}
Fish	1.6×10^{-3}	2,000	8×10^{-7}
Mussels	8.2×10^{-2}	2,000 (a)	4.1×10^{-5}
Shore sand	1.3×10^{-2}	25,000	5.2×10^{-7}
Shore silt	2.0	100,000	2×10^{-5}
Sea bed	6.9×10^{-1}	100,000	6.9×10^{-6}
Ruthenium 106			
Seaweed	4.1×10^{-2}	330	1.2×10^{-4}
Fish	1.0×10^{-3}	1,000	1.0×10^{-6}
Mussels	3.0×10^{-2}	1,000 (a)	3.0×10^{-5}
Shore silt	1.1	100,000	1.1×10^{-5}
Sea bed	1.3	100,000	1.3×10^{-5}
Total beta excluding Ru 106			
Seaweed	1.7×10^{-2}	670	2.5×10^{-5}
Fish	1.3×10^{-3}	2,000	6.5×10^{-7}
Strontium 90			
Seaweed	9.7×10^{-4}	2.7	3.6×10^{-4}
Fish	6.3×10^{-4}	8	7.9×10^{-5}

Note: (a) Same figure taken as for fish although off this coast mussels are not used for food.

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Preliminary work at Dounreay has shown that the dispersion of activity, at least in the region within a few hundred metres of the shore, is less rapid than at Windscale, partly because of the presence of underwater rock barriers parallel to the shore. A further problem is set by the existence in rough weather of a stable spume which is blown in-shore in considerable quantities and carries with it some of the fine particles in suspension near the shore. For these reasons, the permissible discharges were estimated as the result of an experimental series of discharges of fission product solutions from a temporary pipeline near the shore. Supplementary experiments with a fluorescent dye were used to study the movement and dispersion of water in the region of the proposed final pipeline. These studies have shown that discharges of about one-tenth of those possible at Windscale would be completely safe, but that further work, involving prolonged discharges, will be necessary to establish with accuracy the maximum permissible discharge rate.

The experiments off the South Coast were designed first to find the best point from which to make the discharges of liquid waste which will eventually arise from Winfrith Heath, and secondly to study the processes affecting dispersion of effluent in this area. The work has been done with a fluorescent dye released from a ship and is similar to that reported previously at Geneva by Seligman(1). The rates of diffusion have been found to be at least as rapid as those occurring off Windscale, but the situation is complicated by a tendency for the tidal stream to set inshore for much of its flow. The considerable lobster fishing industry, with the resultant handling of gear which spends long periods on the sea bed also introduces factors which are absent at Windscale. Up to the present no radioactivity has been discharged in this area and only a preliminary assessment has been possible. It is estimated that the maximum permissible discharges will be about the same as those at Windscale, but until this has been confirmed by a series of experimental discharges, the radioactivity in the effluent will be restricted to one-tenth of the estimated safe figures.

5. CONCLUSIONS

The results of preliminary hydrographic and biological studies, followed by extensive monitoring of the marine environment during about five years of discharges of radioactivity at a mean rate of about 3,000 curies per month, have shown the following general pattern of dispersal of activity in the sea off Cumberland. The discharged effluent is rapidly diluted with large volumes of sea water and is carried to and fro along the coast over a distance of a few kilometres by the oscillating tidal stream. Beyond the range of this movement, the activity is removed by the process of eddy diffusion and the concentration falls to negligible levels in a few tens of kilometres. Much of the radioactivity becomes adsorbed onto fine particles of sand, mud, and organic matter in suspension and some of this is deposited onto the sea bed. The length of the pipeline is such that the concentration of deposited beta activity on the shore sand is about 50 times lower than that on the sea bed near the effluent outlet. The fish in this area, of which plaice are the most important, live on the sea bed and consequently take up activity from the water, from the

particles, and from the invertebrates which form their food. The activity level in the edible parts of fish is many hundred times less than that in the sea bed and is probably not greatly different from that of the surrounding water. Some of the activity reaching the shore is absorbed not by the sand but by seaweed, and as this weed is used almost directly as a food, stringent limits have had to be placed on its activity. Most of the weed harvested in Cumberland grows within about 20 kilometres of the effluent outlet and there is no substantial dilution by weed from other areas. Consequently maximum permissible discharges are limited primarily by the activity of this weed and by the need to safeguard the small group of people who regularly eat it in quantity.

The results of this experimental programme have shown that it would be safe to release some 20,000 curies per month of fission products at a point about 3 kilometres off this part of the Cumberland coast. Further work now in hand suggests that this figure could reasonably be increased, possibly to as much as 100,000 curies per month. These high figures are possible because the marine processes in this area cause sufficient dispersal to prevent any continuing build up from year to year in the activity levels either in the vicinity of the outlet or in the more widespread regions of the Irish Sea.

Similar discharges of radioactivity are possible in other coastal waters but the safe discharge rates can be determined only by local experiments. Although hydrographic and laboratory studies are of great help in the preliminary assessment of the safe discharge rate, the greatest value must be attached to scientifically planned experimental discharges of radioactivity lasting for a period of at least a few months. These experiments should be continued during the first few years of operational discharges to investigate long period variations and the possibility of a continuing build-up of activity. Thereafter, a much reduced monitoring programme will probably serve to ensure that the conditions remain safe. Such an experimental programme represents a considerable scientific effort and the Windscale programme, covering a period of nearly eleven years, has involved a team varying between about ten and twenty technical staff. It is hoped that the experience gained at Windscale Works as a result of this extended experiment will make it possible to simplify the experiments needed to establish safe discharge rates at other coastal sites.

6. ACKNOWLEDGEMENTS

The work of which the results are reported here has been the responsibility of several groups. The preliminary hydrographic work was arranged by the Atomic Energy Research Establishment at Harwell, and the subsequent assessments were made by the Research and Development Branch, Windscale, who were also responsible for the early part of the experimental programme and for much of the laboratory work on fish and seaweed. The studies of fish movement and landings and of seaweed harvesting and consumption, as well as the rest of the laboratory work on fish, have been carried out by the Fisheries Laboratory of the Ministry of Agriculture, Fisheries and Food. The Health Physics Department of Windscale Works has been responsible both for the general planning of the experimental

discharges and for the sampling programmes. The analytical services for the monitoring programme have been provided by the Chemical Services Department of Windscale Works.

The author is grateful to all these bodies, to the individual workers within them, who provided the data on which this report is based, and to Mr. J. C. Collins who has coordinated the many thousands of individual results which have been summarised in the Tables.

BIOLOGICAL FACTORS DETERMINING THE DISTRIBUTION OF RADIOISOTOPES IN THE SEA.

By

B. H. Ketchum and V. T. Bowen [1]

INTRODUCTION

With the anticipated considerable increase in the peaceful uses of atomic energy the addition of radioisotopes to the sea is inevitable, whether intentionally as a waste disposal measure, or accidentally. The seas are vast and enormous possibilities for dispersion of radioisotopes are available, but it is imperative that the problems associated with radioactive contamination of the oceans be carefully evaluated in advance. The deep sea offers considerable promise for containing large amounts of radioisotopes since it is known that the waters at considerable depths are isolated from the surface layers of the ocean for periods which are measured in terms of centuries. Craig (1957), using 300 years for the mean residence time in the deep sea, has evaluated the ultimate steady state distribution of radioisotopes between the upper layers and the deep water and the rate at which the steady state distribution would be approached if large amounts of fission products were introduced into the ocean below the density gradient (the thermocline).

If considerable amounts of fission products were to be added to the oceans, the ultimate distribution would depend not only upon the current systems and mixing processes which determine the exchanges of water between the deep and the surface layers, but also upon geochemical and biological factors. Many of the elements present in a fission product mixture are insoluble in sea water; these would tend to settle out of the system and not approach equilibrium in the same way that would be expected for soluble materials. Organisms in the water may be expected to accumulate various elements of the fission product mixture to a degree which will depend on the character of the element and the species of organism involved. Part of the accumulation within the organism would depend upon direct assimilation or absorption from the water; part would depend upon the ability of some

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[1] Contribution No. 968 from the Woods Hole Oceanographic Institution.

filter feeding organisms to remove particles from the water. Whether these particles be precipitated fission products or other organisms containing fission products, these elements could also be incorporated into the living tissue. Evidence that marine plankton do concentrate fission products is afforded by observations in the Pacific. Harley (1956) reports determinations of the gross radioactivity of both sea water and plankton organisms to the west of the Bikini test area. The analyses indicate that the gross radioactivity was on the average 470 times more concentrated in the plankton than in the water itself when both are expressed on an equivalent basis.

Once organisms have accumulated a radioisotope they may modify its distribution in a variety of ways. Following their death the organisms may be expected to sink towards the bottom and to carry with them those elements which are tightly bound within the organic or skeletal structures. While living, the organisms may make extensive vertical migrations within the water column, migrations which could transport radioisotopes from a contaminated layer to an uncontaminated zone. The materials which would be transported most effectively by living organisms during migration are those which are readily labile, i.e., those which reach equilibrium rapidly with the dissolved phase. In such a case an organism could accumulate a considerable amount of an isotope while in contaminated water and release most of this accumulation by approaching equilibrium again in uncontaminated water.

In this paper we make a preliminary evaluation of the relative effectiveness of the biological and physical systems in the vertical transport of isotopes in the ocean. From analyses of the elemental composition of various planktonic organisms the effectiveness of biological transport of specified isotopes is also evaluated. Much more needs to be known before a complete evaluation of this problem is possible. The treatment presented in this paper is less in the character of an answer to the problem and more a definition of the types of biological and oceanographic investigations which are necessary before the evaluation can be completed.

ELEMENTAL COMPOSITION OF PLANKTON

The elemental composition of organisms in the sea must be known in order to evaluate the importance of biological transport. The results of spectrographic analysis of eleven samples of marine plankton, mostly single species samples, have been reported by Nicholls, Curl, and Bowen (1958). The results reveal wide differences in the trace element content of different species, and considerable concentration of each element by at least one of the species. It is clear that biological concentration of radioisotopes will depend upon the species of organism and upon the element considered.

For the purposes of this paper we have estimated the con-

centration factors for a variety of radio elements important in nuclear technology for several types of planktonic organisms. The analystical data on organisms are from Nicholls, Curl and Bowen (1958) or are based on analyses published in Vinogradov (1953). The sea water figures are from Vinogradov or from recent separate publications. The genera selected are known to occur in considerable abundance in the sea. The data for the pelagic squid, Ommostrephes, is included since it is known to carry out vertical migrations of several hundred meters in extent. The blank spaces in Table II, plus the fact that many of the values had to be derived from closely related genera or from assumed constant ratios between closely related elements, emphasize the paucity of basic information. The sea water values used give the concentration of the element, so that the actual concentration in the organisms can be calculated.

In general, the concentration factors for radio elements occupy a range of about 10^6, similar to that described by Nicholls et al (1958) for various other elements. The greatest range for a single element among different species is shown by cobalt which varies from a concentration factor of 60 in a salp to 10^4 in Sagitta and Limacina. The concentration factors quoted for iron have been calculated relative to "soluble iron" data of Lewis and Goldberg (1954). They would be lower if total iron were used, but this is variable and should properly be determined on the water from which the organisms were collected. The factors for cesium, on the other hand, are probably low since they are based on the assumption of an unchanged ratio of potassium to cesium in tissues. Chipman et al. (1954) have described much higher levels of radio cesium in oyster tissues, and it seems probable that similar values will be found for some planktonic species.

An estimate for the concentration of cerium by a factor of 10^3 can be derived from Harley's (1956) measurement of cerium^{144} in Pacific macroplankton in comparison with the measurement of the same isotope in Pacific waters by Miyake and Sugiura (1955).

In addition to the concentration factor, which represents the steady state condition, it would be desirable to know the rate at which equilibrium is reached. Unfortunately there seems to be no experimental data to indicate the equilibrium times for the various isotopes in macroplankton. For the above radio elements we estimate that iodine is of very low lability; that cesium and strontium, and, through isotopic exchange, cerium are of very high lability; that for the others rates of exchange ranging from 1 to 15 per cent per hour may be reasonable. The elements transported most readily by vertical migrations will be those most rapidly exchanged with the medium. In contrast, the elements most effectively transported by sedimentation will be those which are tightly bound in the tissues or in skeletal material.

Table I. Concentration factors in some marine organisms (wet weight:volume basis). Values in parentheses are for analyses made on closely related genera.

Elements	Cesium	Strontium	Iron	Cobalt	Zinc	Cadmium	Iodine
Sea water g/cc	5.10^{-10}	9.10^{-6}	4.10^{-9}	$2.5.10^{-10}$	$1.4.10^{-9}$	5.10^{-11}	5.10^{-8}
Organism							
Limacina	$(0.2)^{\pm}$	--	(5.10^4)	10^4	(3.10^4)	(7.10^5)	(5.10^4)
Centropages	0.1-1	--	--	600	--	--	(6.10^3)
Calanus	0.1-1	0.28^x	$2.5.10^4$	200	--	--	100
Ommastrephes	$(0.1)^{\pm}$	$(0.3)^x$	10^4	200	(2.10^4)	2.10^5	(10^4)
Sagitta	--	70	5.10^4	10^4	--	--	--
Euphausia	--	$(0.3)^x$	--	800	--	--	--
Salpa	--	--	--	60	--	--	--

x Derived from Ca analysis and Sr/Ca ratio given by Chow and Thompson (1956).

$^{\pm}$ Based upon analyses for potassium, assuming the Cs/K ratio in the organisms to be the same as that in sea water.

TRANSPORT BY VERTICAL MIGRATION

Planktonic organisms which migrate vertically on a diurnal cycle in the ocean could transport readily labile elements absorbed from the water from layers of high to layers of low concentration. If radioisotopes should be introduced below the thermocline of the ocean in the hope of prolonged retention, the possible transport by this means requires evaluation.

Relative effectiveness of the vertical transport of elements in the sea by biological and physical processes can be evaluated using a simplified model of the distribution which might be expected. This model involves a low or negligible concentration in the upper layer; a higher concentration in the deep layer; and a uniform gradient of concentration through the thermocline or density discontinuity layer. The treatment developed is equally applicable to any other situation in which a layer of high concentration is separated vertically from a layer of low concentration by a uniform gradient. If the organisms migrate from the bottom of the discontinuity layer to the top on a diurnal cycle, the biological transport (T_B) of any given element may be represented by the following:

$$T_B = \frac{\mathcal{E}_o}{\mathcal{E}_\omega} V_o \left(C_b \alpha_b - C_t \alpha_t\right) \frac{d_m}{P_m} \qquad (1)$$

in which $\mathcal{E}_o/\mathcal{E}_\omega$ is the concentration factor (f_o) i.e. the ratio of the concentration of the element in the organisms to the total concentration in the water, V_o is the volume of the organism per unit volume of water, C_b and C_t are the concentrations of the element respectively at the bottom and top of the gradient layer, α_b and α_t are the specific activities of the radioisotope at these two levels, d_m is the distance over which the organism migrates and P_m is the period of migration.

The physical transport (T_p), expressed in finite terms, is given by:

$$T_p = A_z \frac{C_b \alpha_b - C_t \alpha_t}{d} \qquad (2)$$

where A_z is the vertical coefficient of eddy diffusion and d is the depth of the gradient zone considered. The ratio of the biological transport to the physical transport is therefore given by the following:

$$\frac{T_B}{T_p} = V_o \frac{f_o}{A_z} \cdot \frac{d \cdot d_m}{P_m} \qquad (3)$$

Assuming reasonable values for the various parameters the relative importance of biological to physical transport has been calculated with the results shown in Table II. For this computation it has been assumed that $d = d_m = 100$ meters, that the period of migration is 10^5 sec and that the volume of organisms in the water is 1 cc per cubic meter ($V_o = 10^{-6}$). As expected, the relative importance of the biological process increases as the concentration factor within the organism increases, and also increases as the eddy diffusion decreases.

Table II. The ratio of biological to physical transport of elements in the sea for various mixing coefficients and concentration factors, assuming the organism reaches equilibrium for the isotope in the time spent in each layer. Other parameters are defined as follows: $d = d_m = 100$ meters, $P_m = 10^5$ seconds, $V_o = 10^{-6}$ (1 cc/m3).

A_z	$f_o = 1$	10	10^2	10^3	10^4	10^5
.01	10^{-1}	1	10	10^2	10^3	10^4
.1	10^{-2}	0.1	1	10	10^2	10^3
1.0	10^{-3}	10^{-2}	0.1	1	10	10^2
10	10^{-4}	10^{-3}	10^{-2}	0.1	1	10
100	10^{-5}	10^{-4}	10^{-3}	10^{-2}	0.1	1

As shown in Table I, the biological concentration factors range up to values of 10^5. With this concentration factor, and the assumed volume of organisms in the water, the biological transport of readily labile elements will equal the physical diffusion of the element even in moderately turbulent conditions ($A_z = 100$). For very stable conditions in the water ($A_z = 0.1$ or less) the biological transport will equal or exceed the physical transport with concentration factors of 100.

Craig (1957) has calculated the ultimate steady state distribution of radioisotopes which might be added to the deep sea as fission product activities. He used a mean retention time of 300 years in the deep water, from the bottom of the thermocline at 100 meters to the average depth of 3800 meters. The mean transport per day from this layer to the surface is thus:

$$\frac{C_b \times 3.7 \times 10^5}{300 \times 365} = 3.4\, C_b$$

in which C_b is the concentration in the deep water of the isotope considered per cm^3 of water.

The concentration factor necessary to give equivalent biological transport can be computed from our equation (1), assuming a surface concentration of zero initially, and, as above, the depth of migration of 100 meters, a period of one day, and a population of 1 cc/m^3. The resultant concentration factor is 340. Since concentration factors of this magnitude and greater are not uncommon, it seems inevitable that the ultimate distribution of radioisotopes added to the deep sea would be profoundly influenced by the biological processes.

TRANSPORT BY SEDIMENTATION

It has long been known that the distribution of essential nutrient elements in the sea is markedly affected by their assimilation in living tissues, and the subsequent sedimentation of dead organisms, whether intact or as fecal matter of predators. This produces the typically low concentrations in surface layers, where the light is sufficient for photosynthesis, and an increasing concentration with depth below the euphotic zone. Because of the gradient thus developed the physical processes and the transport by vertical migration of plankton must constantly deliver new supplies to the surface. The rate of sedimentation must be sufficient to balance this in areas where a steady state distribution persists.

The downward gravitational transport (T_g) of elements may be expressed, for particles of uniform properties, by the following:

$$T_g = \frac{\varepsilon_o}{\varepsilon_\omega} V_o C_t v \qquad (4)$$

in which v is the settling velocity, which is negative downwards. This process will be most effective for elements which are tightly bound in the organic or skeletal structure of organisms and which, therefore, do not exchange rapidly but await the slower remineralization by bacteria, autolysis or resolution.

This equation can be added to equation (1), the biological transport resulting from vertical migration, to give the combined transport. For particles of uniform properties the rate could be evaluated. However, the particles in the sea are far from uniform, and vary greatly in size, density and shape, all of which will modify the settling velocity. No simple generalization which would provide an evaluation of this process seems possible considering the wide variety of materials which are settling in the sea. Redfield (1955) has shown the results of this process in developing high concentrations of elements in deep waters where surface and deep currents are opposed. In

addition to the nutrient maxima, similar, though generally less extensive, maxima have been reported for other elements, as nickel (Laevastu and Thompson 1956), cooper and zinc (Morita 1952).

RETENTION BY RESISTANCE TO SINKING

Some planktonic organisms aggregate at the surface and thus produce considerable concentrations of trace elements. In "red tide" blooms of the dinoflagellate, Gymnodinium brevis, concentrations of total phosphorus ten times greater than the maximum in adjacent waters were described by Ketchum and Keen (1948). Collier (1953) also observed unusually high concentrations of zirconium and titanium in a similar bloom. These blooms tend to occur in surface lenses of low salinity (see Slobodkin 1953) so that physical transport is minimal, and the toxicity of the bloom would minimize grazing and transport of the elements away from the center of concentration.

The observed accumulation of elements in such plankton blooms are clearly the result of the unique properties of the organisms involved. These tend to aggregate at the surface, either by migration or flotation. Greater concentrations may subsequently be achieved, as discussed by Ryther (1955), along convergences at the surface.

Those articifical radioisotopes which are now found in the sea have been added at the surface as fallout from weapons tests. Analyses of surface sea water have shown a striking enrichment of cerium or promethium relative to strontium. This has been demonstrated near Bikini by Miyake and Sugiura (1955) and in both the north and south Atlantic by Bowen and Sugihara (1958). Harley's (1956) radiochemical analyses showed that the ratio of Ce^{144}: $Sr^{89,90}$ was higher in the macroplankton than in the water.

The microplankton will preferentially concentrate the rare earth "radio colloids" even more than the macroplankton. Bowen and Rubinson (1951 and unpublished) have shown that yeast cells act as very efficient collecting surfaces for these materials, and Rice (1956 and unpublished) has demonstrated considerable accumulations of yttrium and cerium by cultures of planktonic algae. A large fraction of the microplankton population can maintain its position in the upper layers, thus resisting both sinking and physical eddy diffusion, which in this case would transport elements downward from the higher concentrations at the surface. Since the rare earth elements are concentrated more actively than strontium by three or four orders of magnitude their accumulation by phytoplankton would produce the observed retention in the surface water.

DISCUSSION

The treatment presented above appears to us sufficient to show that the movements of organisms and their activities as concentrators of elements will be of real quantitative significance in modifying any concentration gradients created by the addition of radioisotopes to the sea. Adequate data are presented to indicate that estimates of vertical transport based upon physical considerations alone may be in error by a factor of two or more. Since the affinity of organisms for individual isotopes differs widely, preferential transport by the biological agents may be expected.

Ultimate evaluation of the problem requires basic information which is unavailable as yet. The paucity of information is apparent in both the rate of physical processes of mixing and exchange between different layers in the ocean, and in the biological field concerning the distribution of organisms and their affinity for various radio elements.

The physical oceanographers are unable as yet to define the coefficient of eddy diffusion precisely enough to allow intercomparison of a variety of places. The biological transport of elements may augment the physical transport or oppose it, and it is, therefore, essential in each case to evaluate both processes. For this reason we have, where possible, expressed the biological transport in terms of what may be expected from physical mixing. The values for the mixing coefficient used in calculating relative transports in Table II range from very stable to moderately turbulent conditions. Values less than unity are typical of conditions in the gradient layer of the open sea, and values of 100 or more may be observed in turbulent coastal waters. For a complete evaluation of the vertical transport of elements much more precise data on vertical eddy diffusion in the sea are required.

It is equally true that the biological oceanographers do not have adequate data to evaluate the concentration of organisms to be expected in various areas at various times of the year. We do know that the biological sampling techniques with nets do not collect all of the populations but that the value of 1 cc per cubic meter used in the above examples is common in coastal areas and is not infrequently found in the open sea. In the Sargasso Sea, and in other comparable marine "deserts", however, the populations rarely exceed one tenth of this value. In such areas the physical mixing processes are also very small.

The basic biological information needed includes all stages of the ecological cycle in the sea, i.e., the biomass of various populations, the rate of reproduction and the exchanges of energy and of elements from one component of the community to another. For problems of sorption, not only the biomass but

also the surface area must be known. This is particularly true of the microplankton which afford by far the greatest surface area in the open sea where other suspended materials are rare. The size, density and shape of the organisms determine settling rates which control the downward transport of elements by sedimentation.

The importance of determining the accumulation of various elements by different species of plankton cannot be overemphasized. The data already available suggests considerable concentration by at least one species of each element which has been studied. The effectiveness of transport depends, in each case, on both the concentration factor and on the rate at which the organism reaches equilibrium with materials in the water. Extensive studies of the rates of uptake and exchange are needed, since this information is available in very few instances.

REFERENCES

Bowen, V. T. and Rubinson, J., Uptake of lanthanum by a yeast, Nature 167:1032, (1951).

Bowen, V. T. and T. G. Sugihara, Marine geochemical studies with fallout radioisotopes, (in prep.).

Chipman, W. A., T. R. Rice and T. J. Price, Accumulation of fission product by marine plankton, fish and shellfish, U. S. Fish and Wildlife Radioisotope Lab. Progress Report, July-December, (1954).

Chow, T. J. and T. G. Thompson, Flame photometric determination of strontium in sea water, Anal. Chem. 27:18-21, (1955).

Collier, A., Titanium and zirconium in the bloom of Gymnodinium brevis Davis, Science 118:328, (1953).

Craig, H., Disposal of radioactive wastes in the ocean: The fission product spectrum in the sea as a function of time and mixing characteristics, Chapt. 3. In: The effects of atomic radiation on oceanography and fisheries. Pub. No. 551, Nat. Acad. of Sci. -Nat. Res. Counc. 34-42, (1957).

Harley, J. F. (Editor), Operation Troll, U. S. Atomic Energy Comm., New York Operation Office, v + 37 pp., (1956).

Ketchum, B. H. and D. J. Keen, Unusual phosphorus concentrations in the Florida "red tide" sea water, Jour. Mar. Res. 7:17-21, (1948).

Lewis, G. J., Jr. and E. D. Goldberg, Iron in marine waters, Jour. Mar. Res. 193(2):183-197, (1954).

Laevastu, T. and T. G. Thompson, The determination and occurrence of nickel in sea water, marine organisms and sediments, J. du Conseil 21:125-143, (1956).

Miyake, Y. and Y. Sugiura, Radiochemical analysis of radionuclides in sea water collected near Bikini Atoll. Pap. Met. Geophy., 7(1):33-37, (1955).

Morita, Y., Copper and zinc in Pacific waters, Rec. Oceanographic Works in Japan 1:49-51, (1953).

Nicholls, G.K., H. Curl, Jr., and Bowen, V. T., Spectrographic analyses of plankton, Limnol. and Oceanogr.,(in press).

Redfield, A. C., The hydrography of the Gulf of Venezuela. Pap. Mar. Biol. & Oceanogr., Deep-Sea Res. Suppl. 3:115-133, (1955).

Rice, T. R., The accumulation and exchange of strontium by marine planktonic algae, Limnol. and Oceanogr. 1(2):123-138, (1956).

Ryther, J. H., Ecology of autotrophic marine dinoflagellates with reference to red water conditions, In: Luminescence of Biological Systems, 387-414, (1955).

Slobodkin, L. B., A possible initial condition for red tides on the coast of Florida, Jour. Mar. Res. 12(1):148-155, (1953).

Vinogradov, A. P., The elementary chemical composition of marine organisms, Memoir Number Two, Sears Found. Mar. Res., New Haven, Conn., pp. 647, (1953).

THE DISPOSAL OF RADIOACTIVE WASTES INTO THE ATLANTIC AND GULF OF MEXICO COASTAL WATERS OF THE UNITED STATES

A Report of a Working Group of the Committee on Oceanography of the National Academy of Sciences-National Research Council, as Reviewed and Endorsed by the Committee on Effects of Atomic Radiation on Oceanography and Fisheries.

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SUMMARY

A study has been made of the feasibility of using selected areas in the Atlantic and Gulf of Mexico coastal waters of the United States as receiving grounds for the disposal of packaged, low level radioactive wastes.

The primary objective of the study has been to provide an estimate of the rate of return of radioactive substances to man, arising from stated rates of disposal into the coastal areas. The limiting rate of disposal has been taken as that which through a combination of physical and biological processes will return the radioactivity to man at a rate equal to the maximum permissible rate of ingestion of a given radionuclide in drinking water.

These rates were based on the occupational maximum permissible concentrations, MPC, in Handbook 52. The MPC's for the general population, according to present information, should be lowered by a factor of 10. The revised MPC's of some isotopes may be reduced even further. It is believed, however, that the conservative assumptions contained in this report off-set the effects of these reductions in MPC values.

The present practice of using 55 gallon steel drums as disposal canisters containing the waste mixed with concrete is estimated to provide containment of approximately 10 years, during which time radioactive decay will have destroyed all radioisotopes (based upon ORNL current rate of production and shipment) to below hazardous levels, with the exception of Sr 90, Cs 137, and possibly Co 60.

Coastal circulation is not known in sufficient detail to provide quantitative estimates of the rate of transport of a contaminant out of any of the areas selected as possible disposal sites. These estimates can be made only after detailed circulation studies have been made. Especially lacking is knowledge of the circulation of bottom waters. Nevertheless, several areas stand out as being probably unsuited as disposal sites. They are the coastal estuaries and bays, and the regions immediately seaward of these areas. Shoreward transport

along the bottom in these regions would tend to intensify the rate of return of a contaminant to man. Also, a region southeast of Long Island, extending out to approximately 50 fathoms, appears to have restricted bottom circulation during the summer months and therefore might accumulate larger quantities of contaminant than other coastal areas.

A theoretical study of the dilution of contaminant by turbulent mixing processes has been made. The results of the study provide the means of evaluating the effects of changing environmental parameters and of various disposal methods on the dilution of a contaminant. **Because of the assumptions made, all estimates of concentration are probably higher by at least a factor of ten than would actually exist in practice. Even with these conservative assumptions calculations show that given a rate of disposal of 100 curies per year of uncontained waste into water 30 meters deep with a current of 5 miles per day, the maximum concentration of waste which will appear one kilometer (approximately 5/8 miles) from the disposal site will be 2×10^{-7} uc/ml, a concentration that is lower than the maximum permissible concentration of Sr 90 in drinking water.** Sr 90 has the lowest MPC value of all radioisotopes listed. In addition, the relationships between relative concentration and both time after release and distance from the disposal site, under the unlikely condition that no current will aid in diffusive mixing, have been developed.

In arriving at recommended disposal rates the interaction of a contaminant with suspended solids and bottom sediments has been neglected. It was found impossible to make a quantitative estimate of the magnitude

of this reaction. Neglecting this factor puts a certain factor of safety in the recommendations, as sorption onto bottom sediments within the disposal area will provide additional containment, thus allowing for further destruction of the contaminant by radioactive decay. In the case of disposal into areas productive in commercially important shellfish (oysters, clams, etc.) the sorption onto bottom deposits may become a potential hazard rather than a safety factor. This situation has been eliminated by selecting areas in which no shell fisheries occur.

The return of radioactive wastes to man by ingestion of contaminated marine food products is considered to be the most likely potential source of hazard that could result from disposal into coastal waters. An estimate has been made of the maximum permissible concentration of each of several radioisotopes in sea water, below which contamination of marine food products will not lead to greater than allowable intake humans whose sole source of protein is fish. This estimate was derived from the maximum permissible concentration of the isotopes in drinking water, from which was computed the maximum weekly intake of each of the isotopes; the weekly ingestion rate of fish, taken as 1.5 kg, a value that is high compared with the per capita value for this country but has been taken on the assumption that some individuals obtain all of their protein from fish; and the extent to which marine organisms can concentrate the various isotopes within themselves above the level in their environment. The most hazardous isotope in the list is Sr 90, for which the maximum permissible concentration in sea water

is 8×10^{-7} uc/ml, which by coincidence is identical with the MPC value for drinking water.

Suggested disposal areas have been chosen in an attempt to minimize conflict with submarine cable operation, as well as the purely mechanical problems connected with fisheries activities.

RECOMMENDATIONS

The panel is of the opinion that certain Atlantic and Gulf of Mexico coastal areas can be used as receiving waters for the controlled disposal of packaged, low level, radioactive wastes.

Twenty-eight possible locations have been selected (figure 8, p. 51) that could, on the basis of presently available information, be used without limiting our other uses of coastal waters. The actual choice of disposal areas should be undertaken within the following limitations:

1) Prior to start of disposal operations a pre-use survey of an area must be made to determine details of local circulation and an inventory of the biota, especially of bottom-living organisms.

2) The total quantity of activity that is deposited into any one disposal area in any one year should be limited to 250 curies of Sr 90 or the equivalent of other isotopes. For the equivalent amounts of other isotopes see Table II and the accompanying discussion on p. 20.

3) The quantity of activity that is deposited in any one area during any given month should be limited to 100 curies of Sr 90 or the equivalent of other isotopes.

4) Adjacent disposal areas should be separated by at least 75 miles.

5) No 300 mile section of coast line should contain more than three disposal areas unless predominant currents, both bottom and surface, indicate that no exchange between areas is possible.

6) The waste container should be of such construction that no part of it or its contents will float to the surface should the container be broken. The practice of using steel drums as containers is recommended as giving appreciable holding time in the disposal area.

7) Periodically during use, the area should be monitored to provide a measure of the spread of radioactivity throughout the region including both the biota and the bottom sediments, and to note changes that might be caused by disposal operations. The results of this monitoring may indicate that certain of the above assumptions should be changed.

THE PROBLEM

The U.S. Atomic Energy Commission has asked the Committee on Oceanography of the National Academy of Sciences-National Research Council to study the feasibility of disposing of low level, packaged, radioactive wastes into the on-shore waters of the Atlantic and Gulf of Mexico coasts of the United States. The areas of special interest are closer to shore than the present designated areas now 100 and more miles out.

The objectives of the study are to recommend locations that can safely be used as disposal areas, together with the limitations on quantity and kinds of radioactive materials, rates of disposal, and other pertinent factors necessary to keep the concentration of radioactive substances within permissable levels.

Of special interest is the use of near-shore regions as disposal areas for the low level radioactive wastes generated in university and industrial laboratories, hospitals, and research institutions licensed by AEC to use relatively small quantities of radioactive materials.

We emphasize here the term low level wastes. These are broadly classified as wastes containing up to the equivalent of millicurie quantities of activity per gallon. They are distinct from high level

wastes, such as those obtained from the processing of spent reactor fuels which may contain hundreds of curies per gallon. The present study is not concerned with the disposal of high level wastes.

PRESENT SEA DISPOSAL PRACTICES

With the increasing quantities of radioactive materials that have been used in peacetime applications by both AEC and non-AEC institutions there has been a corresponding increase in the quantities of low level wastes that have no further usefulness, but because they do represent a potential health hazard cannot be disposed of by conventional methods (municipal incinerators, sanitary dumps, etc.). In the past, much of this waste material has been packaged and dumped into designated areas approximately 200 miles off the Atlantic Coast in approximately 1000 fathoms of water. Much of the material has been carried to the disposal areas by naval vessels during scheduled disposal of non-radioactive wastes. In addition, civilian waste disposal concerns, licensed by AEC, have dumped small quantities of low level wastes into coastal waters in areas normally used as receiving areas for non-radioactive wastes. Recently AEC received several new requests for the licensing of civilian marine disposal concerns.

Table I and figure 1 summarize the sea disposal operations that have been conducted along the Atlantic Coast since 1951 (1). It should be emphasized that the quantities of activity listed were not measured at the time of disposal to the sea. At best, they were measured at the time of packaging of the wastes, and frequently the values reported are estimates made by the users of the material who

listed the total amount of activity shipped to them, with no allowance made for losses during use and for radioactive decay. The quantities listed are therefore, unquestionably, larger than the quantities actually deposited in the disposal areas.

These disposal operations can be divided into three broad subdivisions, using the immediate source of the wastes as a criterion. They are:

1. Low level wastes generated within AEC facilities.

These constitute, by far, the largest quantities of radioactive materials that have been deposited in the Atlantic disposal areas. Since 1951, 5870 curies of a variety of isotopes contained in 8432 fifty-five gallon drums have been disposed of. A rather insignificant fraction of this total was deposited in the designated area approximately 200 miles due east of Cape Cod, area a, figure 1. Most of it has been added to the disposal area approximately 200 miles east of Cape May (Delaware Bay), area b, figure 1.

The AEC has described the general nature of these wastes as follows (1):

> "AEC wastes which are dumped at sea are heterogeneous in character and as a rule contain quantities of activity normally associated with laboratory experimentation and with decontamination operations. For the most part, they consist of solid materials such as paper wipes, rags, mops, ashes, animal carcasses and contaminated laboratory paraphernalia. Some liquids containing radioactivity in the concentration range of microcuries per liter have been incorporated in cement mixtures or with chemical gelling materials prior to packaging and dumping. Because the wastes and their contaminating radioisotopes are heterogeneous in character, it is difficult to determine accurately the total quantities of radioactivity involved."

Most of these wastes have been packaged in fifty-five gallon

drums with added concrete to insure proper bulk density. The AEC has set specifications (1) (2) for the packaging and handling of contaminated scrap.

2. Low level wastes generated within non-AEC government operations.

Four agencies (the National Bureau of Standards, the Naval Ordinance Laboratory, the Naval Research Laboratory, and the National Institutes of Health) all in the Washington, D.C. area, have since 1955 generated approximately four curies of heterogeneous wastes that have been deposited in a designated disposal area, approximately 75 miles east southeast of Cape Henry (Chesapeake Bay), by the U.S. Coast Guard. This is area c, figure 1. The U.S. Fish and Wildlife Service, Beaufort, N.C., has disposed of less than 0.2 of a curie of heterogeneous wastes, in area d, figure 1, approximately 8 miles off-shore from Beaufort, North Carolina.

3. Low level radioactive wastes generated within non-governmental facilities.

Several industrial concerns and research laboratories licensed by AEC to use radioactive materials have either conducted their own waste disposal operations or have contracted with licensed marine disposal companies to have the wastes carried to sea. The areas in which low level radioactive wastes have been dumped at sea by these operations are the unlettered areas in figure 1. Approximately 25 curies have been disposed of through these channels, most of it several hundred miles off shore.

In all, something less than 6000 curies have been added to the water off the Atlantic coasts of the U.S. between 1951 and 1958. The exact composition of this waste material is uncertain; that is, it is impossible to determine the quantities of various radioisotopes, and in many cases the total activity

associated with a disposal container is uncertain. By far the greatest bulk of this material has been deposited into water 1000 fathoms or more deep, and in containers that will provide some factor of safety to the environment, in that at least a part of the wastes will have disappeared by natural radioactive decay before being released to the sea.

A survey of the area that has received most of the wastes, area b, figure 1, was made by the Chesapeake Bay Institute of The Johns Hopkins University, and the U.S. Coast and Geodetic Survey. The activity, beta and gamma counting, of samples of bottom sediments taken within the disposal area was compared to the analysis of samples taken outside of the area. No difference could be found. Comments on survey methods will be made in a later section.

The quantity of low level radioactive wastes that will, under existing operational procedures, find its way into the Atlantic coastal waters is increasing. The off-shore, deep water disposal areas appear to be adequate to handle projected quantities of these wastes without limiting our other uses of these waters. Of immediate concern to the AEC is the increase in the quantities of radioactive materials used by non-governmental agencies and the increase in the numbers of commercial marine disposal concerns who are seeking licenses to handle and dispose of the low level radioactive wastes into shallow coastal areas.

In general, marine disposal concerns are at present not equipped to carry the wastes several hundred miles to sea, at least not without a considerable increase in the cost of the service. The disposal concerns would like to deposit these wastes in existing or newly designated disposal areas in the relatively shallow coastal waters

up to approximately fifty miles from shore. One concern has, with AEC permission, disposed of limited quantities of packaged low level wastes in 50 fathoms of water, some twelve to fifteen miles from the coast, area e, figure 1.

4. Estimate of the fraction of the production of Oak Ridge National Laboratories shipped to non-AEC operations, that became wastes for sea disposal.

During the period January 1956 to September 1957, ORNL shipped approximately 50,000 curies, measured at the time of shipment, for use by non-AEC facilities. Of this total, approximately 28,759 curies were isotopes with short half lives, while isotopes of strontium, cobalt, cesium, iron, and zinc amounted to 21,141 curies, of which 21,020 were shipped as "sealed sources". Assuming that sealed sources (cobalt bars, for example, used as radiation sources) will not find their way into commercial disposal routes when their initial usefulness has passed, 121 curies of long-lived isotopes appear as the potential supply that might have arrived at dockside for disposal at sea. During the same period, an estimated 25 curies (composition doubtful) was actually disposed of at sea.

If the assumption concerning the fate of "sealed sources" is correct and if the estimate of 25 curies disposed of at sea is correct, then approximately 20% of the ORNL shipments of "hazardous isotopes" to non-AEC users will eventually appear as wastes for sea disposal.

TABLE I

PAST AND PROJECTED AMOUNTS OF RADIOACTIVE MATERIALS DISPOSED IN ATLANTIC OCEAN

Origin	Quantity (curies)		Location (Fig. 1)
	1951 to 1958	1958 to 1963 (est.)	
AEC wastes, disposed by U.S. Navy	5870	-	a, b
Government agencies, non-AEC, disposed by U.S.Navy and Coast Guard	4.3	531.9	b, c
University and industrial labs. Disposed by private concerns	10+	25+	d, e, f and unlettered

Data from reference (1)

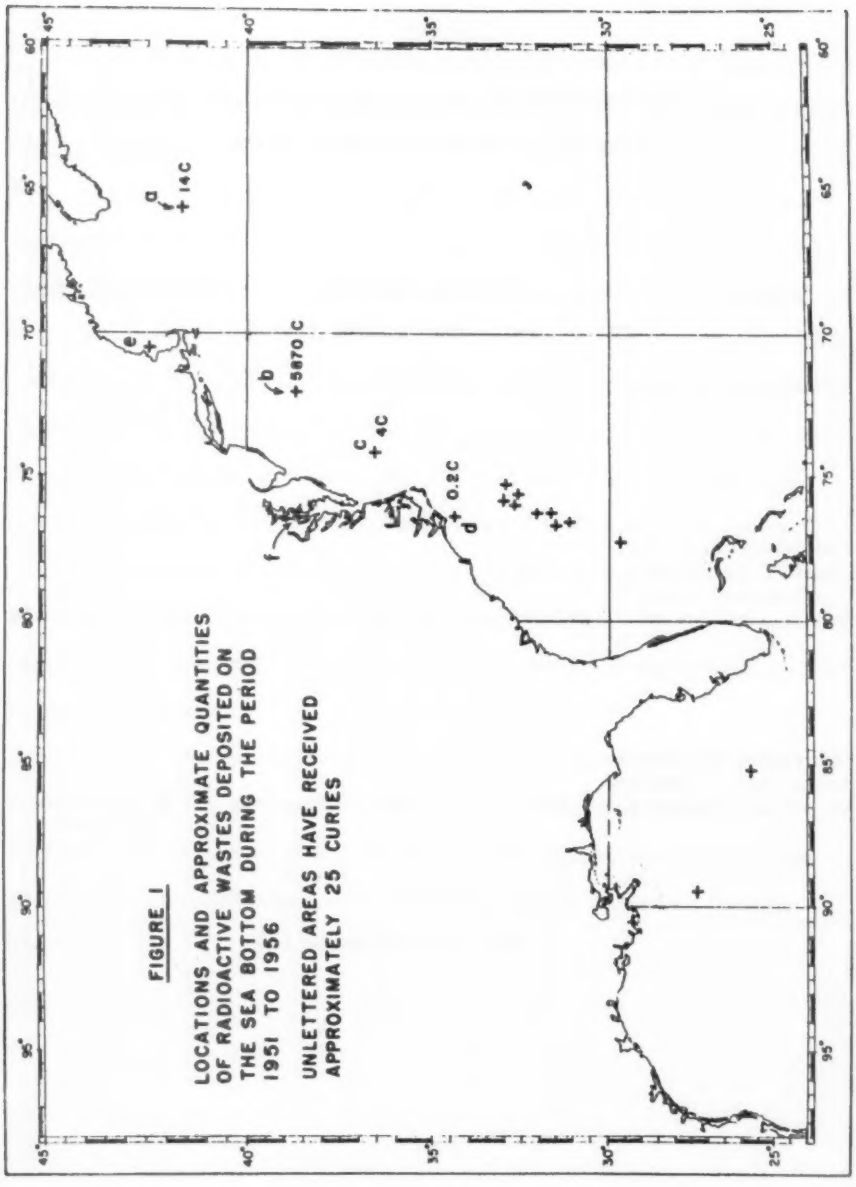

FIGURE I

LOCATIONS AND APPROXIMATE QUANTITIES OF RADIOACTIVE WASTES DEPOSITED ON THE SEA BOTTOM DURING THE PERIOD 1951 TO 1956

UNLETTERED AREAS HAVE RECEIVED APPROXIMATELY 25 CURIES

PREVIOUS STUDIES

Several studies have been made since 1950 that are either directly or indirectly concerned with the disposal of radioactive substances into the sea. The first of these, published as U.S. Bureau of Standards Handbook 52 (3) lists the quantities of each of a number of radioisotopes that can be safely retained in the body, as well as the concentration of each isotope that can be tolerated in drinking water and in air. The maximum permissible body burden, drinking water and air concentrations are considered to be the levels below which no readily detectable biological damage will occur in man under conditions of continual exposure at those levels.

Although the recommendations contained in Handbook 52 were based upon the best biological and radiological evidence available, the authors note that in several cases the evidence available to them was scant and that the maximum permissible concentration levels should be revised as new evidence becomes available. In this connection Looney (9) suggested that the accepted level for radium, which forms the basis (in part) for the calculation of the permissible levels of other isotopes, is too high and recommends that the radium level be lowered until more information becomes available on the effects of radium in man over a normal lifetime.

In calculations made later in this report, the recommended maximum permissible levels in Handbook 52 have been used. We realize that man does not drink seawater; however, the Handbook 52 values give a basis for estimating the maximum permissible rate of ingestion of radionuclides that may be contained in marine food products.

In 1954 a study was made by the sub-committee on Waste Disposal and Decontamination of the National Committee on Radiation Protection, of the problems connected with the disposal of radioactive materials in the ocean. This study was published as Handbook 58 of the National Bureau of Standards (4). Although Handbook 58 does not make specific recommendations with regard to disposal site locations, rates of disposal, etc., it does recommend that all radioactive wastes that are to be disposed of into the sea be packaged and that disposal be into water at least 1000 fathoms deep. These two recommendations form the basis for present AEC sea disposal regulations. In addition, Handbook 58 enumerates the physical, chemical, and biological factors thought to be important in regulating the dispersal of a contaminant throughout the oceans. However, because of lack of quantitative information, no attempt was made to combine the various factors to obtain an estimate of the level of contamination of the ocean and marine food products associated with stated disposal practices.

In 1956 the National Academy of Sciences-National Research Council organized six committees to study various aspects of the biological effects of atomic radiation. The report of one of these Committees, the Committee on the Effects of Atomic Radiation on Oceanography and Fisheries, was published in 1957 as Publication 551 of the National Academy of Sciences-National Research Council (5).

Publication 551 gives a detailed account of the state of knowledge of the physical, chemical, biological and geological factors involved in the interaction of radioactive wastes, especially fission

product elements, with the marine environment. While much of this study is concerned with the deep oceans, and the massive quantities of materials that will be produced as a result of nuclear power production, it is, nevertheless, a useful guide in the attempted solution of all problems concerned with radioactive wastes and the marine environment.

Following the 1956 meetings of the Committee on the Effects of Atomic Radiation on Oceanography and Fisheries, but before Publication 551 was completed, a meeting of several scientists from the United States and the United Kingdom was held, at which there was a liberal exchange of information concerning the problems of the disposal of radioactive wastes to the oceans. At that meeting it was learned that the British Atomic Energy Authority plant at Windscale, on the Irish Sea, was discharging low level liquid wastes through a three mile long pipeline, directly into the Irish Sea, with authorization to discharge at the rate of 1000 curies per month. The basis for the authorization was the results of a series of studies giving: (1) the detailed circulation of the Irish Sea area immediately seaward from the Windscale plant; (2) the uptake of activity by migratory fish that pass through the area; (3) the contamination of an edible seaweed that is harvested in an adjoining area, estimated from the circulation study and uptake experiments; and (4) the level of contamination of local beaches, estimated from the circulation study.

It is now believed that as a result of monitoring studies made during the build-up to the 1000 curie per month discharge level, and a reassessment of the "safety factors" that were included in the original studies and recommendations, authorization has been given to discharge at the rate of 10,000 curies per month.

A summary of the discussions at the meeting has been distributed under the title "Report of a Meeting of United Kingdom and United States Scientists on Biological Effects of Radiation in Oceanography and Fisheries", National Academy of Sciences-National Research Council, October 31, 1956 (6). A portion of that report is quoted below, as it has direct bearing on the studies of the present committee.

Disposal into Coastal Waters

> Maximum quantities and rates of disposal of radioactive substances into coastal waters are set, in all cases, by two considerations. The first is the transfer of these substances back to man and his surroundings. The second is the effect upon the marine resources and environment.
>
> Bulk Liquids
>
> In coastal waters it will, in general, be possible, in proper circumstances, to dispose of wastes in dilute liquid form, but the permissible quantities of radioactivity in such wastes may be expected to vary considerably from one area to another because of the diverse nature of coastal situations.
>
> A careful study is required to determine the safe quantity of each isotope in each situation, including the details of the physical, chemical, and biological factors, and the habits of the human population potentially affected.
>
> Continuing studies are required at each disposal locality to insure safety, to determine ultimate steady state conditions, and to detect possible long term variations arising from variability of the environment.
>
> Such investigations have been carried out over a number of years in the Irish Sea and the results indicate that fission products can be safely released in that area at an average rate of several hundred curies a day; it appears likely, therefore, that similar quantities of waste could be safely liberated in some other areas.
>
> In selecting locations for nuclear installations the waste disposal problems should be taken into account. Because of the additive effects of wastes independently discharged into the same water mass, the proximity of other facilities is an important consideration.

Packaged Wastes

Packaged liquids and sludges in containers which can rupture and thus liberate their contents to the sea, and solid materials of density greater than sea water may also be safely disposed of in coastal waters if proper precautions are observed. The amount of activity which is dissolved in the sea water, or taken up by organisms, from such materials is subject to the same limitations as for bulk liquid wastes.

Precautions must be taken to guard against recovery by fishing or salvage operations, or transport to areas where the material could constitute a hazard. Disposal areas for such wastes should be in designated locations, and all disposal should be adequately recorded and controlled.

THE PRESENT PROBLEM

The basis for judgment.

The request from the Atomic Energy Commission asks essentially for a differentiation between safe and unsafe procedures related to the dumping of radioactivity into coastal waters.

The determination of where safe procedures end and unsafe procedures begin involves an evaluation of information in two very different fields of science. The first is radiation biology, a field that can supply information concerning tolerance limits for the quantities of radioactive materials that man can have either in his immediate environment or within himself, without regard for how it gets there. The second science field is oceanography, which can supply a description of the processes that can bring radioactive substances from a marine disposal area back to man.

We emphasize here that the very nature of the primary information upon which our evaluation is based makes the division between safe and unsafe disposal procedures a rather broad region rather than a sharp dividing line. Because of this we have, with purpose, adopted a con-

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servative attitude in our integration of the many pieces of information that make up our conclusions.

Radioactive substances are a potential hazard to man, (1) because of radiation received from the immediate environment (external emitters), and (2) because of radiation received by substances taken into the body by ingestion, inhalation, or absorption through the skin (internal emitters). In both cases the potential hazards may do damage to the individual so as to reduce the life span, impair the functioning of parts of the body, etc., i.e. pathological damage, or to increase the mutation rate which will alter the inherited characteristics in future generations, i.e. genetic damage.

Our present state of knowledge with regard to the pathological effects of radiation is given in detail in NAS-NRC Publication 452 (7). A summary report of the National Academy of Sciences-National Research Council Committee on the Genetic Effects of Atomic Radiation was published in 1956. (8).

The separation of safe from hazardous sea disposal procedures must be made, first of all, on the basis of potential hazard to man through his normal utilization of the sea, and secondly, on the possibility of injurious effect produced in the marine environment itself.

Our assessment of the quantities and the rates of disposal of low level radioactive wastes into in-shore water that will create a potential hazard to man, through his uses of the sea and marine products, developed from consideration of the natural processes occurring in the marine environment that could bring the radioactive wastes back to man from suggested disposal sites. We have recognized two mechanisms that

appear to be the most likely avenues through which this could occur. They are: (1) transport of the radioactive wastes from the disposal sites to the immediate shoreline, thereby creating a potential hazard in man's recreational uses of the coast, and (2) uptake of the radioactive waste components by one or more of the trophic levels in the marine biota with return to man in commercially important fish and shellfish.

We would emphasize at this point that in all cases our separation of hazardous from non-hazardous procedures so far as man's tolerance for radiation is concerned, is based upon the Handbook 52 values for maximum permissible amounts of radioisotopes in the total body and maximum permissible concentrations in water. The latter are for drinking water or for submersion in contaminated fluids. These values consider only pathological effects. No evaluation of possible genetic damage was attempted when Handbook 52 values were compiled. The conclusions in this report, then, may need revision if Handbook 52 maximum permissible levels are drastically altered, or when some of the uncertainties introduced by lack of information in our evaluation of the oceanographic factors become better known. However, since Handbook 52 values are thought to be conservative and since our analysis of the oceanographic factors presents a conservative estimate of the behavior of the environment, as will be described below, we believe disposal practices based upon our recommendations have little likelihood of producing a hazard to man's present uses of the coastal waters.

In the reports of quantities of radioactive substances already disposed of at sea one usually finds only the number of curies recorded. Only infrequently are the isotopes listed. Although this is unavoidable in many cases, a knowledge of the curie content of a disposal container only partially defines the potential hazard of the material. The extreme variability in the maximum permissible concentrations of various isotopes in drinking water (3), for example, 2×10^{-1} and 8×10^{-7} $\mu c/cc$ for tritium and strontium 90 respectively, emphasizes this point.

In the discussions which follow we will be concerned primarily with strontium 90. The hazard of other isotopes, relative to strontium 90, insofar as uptake by marine organisms and return to man in marine food products is concerned, will be given by the ratio of the permissible sea water concentration of an isotope to that of strontium 90. Table II lists the number of curies of each of a group of selected isotopes, equivalent to 250 curies of strontium 90, the latter value being the suggested maximum yearly rate of disposal of strontium 90 into any one disposal area. Also shown are the quantities of each of the isotopes that would decay to 250 equivalent curies following containment of one month and of one year.

The significance of the quantities of isotopes relative to Sr 90 is apparent when considering the practical problem of the disposal of packages containing a mixtuse of isotopes. Assume for example that packages containing wastes of the following composition have been added to a disposal area; 525 curies of Na 24, 1000 curies of Ca 45, 100 curies of Fe 59, 100 curies of Co^{60}, 120 curies of Sr 90 and 1000 curies of Cs^{137}, the total number of curies amounts to 2,845, well over the suggested yearly limit of 250 c of Sr 90. Obviously the relative hazard to man considered in the route that might return the waste to him from the disposal area through marine food products will be less for the mixture than for Sr^{90}. If the quantity of each of the isotopes above are multiplied by the ratio of the maximum permissible sea water concentration of Sr^{90} to that of the isotopes, then the sum results assuming no containment is approximately 148 curies.

The figure which is a more realistic measure of the potential hazard of the wastes than the 2845 curies includes the effect of MPC values for each isotopes and the concentration factors from sea water to marine food products.

TABLE II

Quantities of Selected Radioisotopes Equivalent[1] to 250 Curies of Strontium 90, Showing the Initial Quantities that Will Decay to 250 Equivalent Curies Allowing One Month and One Year Containment.

Isotope	Curies		
	no containment	1 mo. containment	1 yr. containment
Na 24	5.0×10^{7}	10^{24}	10^{183}
P 32	15.5	68.6	1.1×10^{9}
S 35	3.1×10^{6}	3.9×10^{6}	5.6×10^{7}
K 42	3.1×10^{6}	10^{14}	10^{226}
Ca 45	1.6×10^{5}	1.8×10^{5}	7.5×10^{5}
Fe 59	1.2×10^{3}	1.9×10^{3}	3.3×10^{5}
Co 60	6.2×10^{3}	6.3×10^{3}	7.0×10^{3}
Cu 64	5.0×10^{4}	10^{21}	10^{201}
Zn 65	1.4×10^{4}	1.5×10^{4}	3.8×10^{4}
Sr 90	250	250	250
I 131	9.3×10^{2}	1.2×10^{4}	10^{16}
Cs 137	9.3×10^{4}	9.3×10^{4}	9.3×10^{4}

(1) Equivalence based upon ratios of Permissible Sea Water Concentrations.

Why dispose at sea?

There are two ways of handling radioactive materials to prevent them from becoming a hazard to man. One is by containment, which has as its objective the retention of the material in such a manner that it does not get into the human environment, at least until natural radioactive decay has reduced the quantity of material to below permissible levels. The other is by dispersal, which has as its objective the dilution of the waste to below permissible levels before it becomes a part of the immediate human environment.

Within limits, procedures can be established so that disposal into coastal waters can take advantage of some of the desirable features of both methods of handling the wastes. The advantage of containment can be achieved by proper canister design. Presently used canisters are reclaimed 55 gallon steel drums which have an expected life, so far as corrosion by sea water is concerned, of approximately ten years (10).

The factor of safety introduced by ten year containment is shown in Table III, in which the percents of the initial activity remaining after ten years and the maximum permissible concentrations for drinking water are listed for a group of isotopes including high yield, long-lived fission products and the isotopes that are shipped from Oak Ridge National Laboratories to licensed users.

Two features of Table III should be emphasized. First, isotopes having long half life, that is, relatively large amounts remaining after ten years, and low MPC values are those that may produce the greatest potential hazard to man. Second, the MPC values are drinking water

values and we are concerned here with sea water. Although not directly applicable to the present problem, these MPC values will be used later in modified form.

TABLE III

Percentages of Initial Activity Remaining After Ten Year Containment and Maximum Permissible Concentrations for Drinking Water, for Selected Fission Product Elements and ORNL Isotopes

Isotope	Percent after 10 years	MPC (3) (uc/ml)	Isotope	Percent after 10 years	MPC (3) (uc/ml)
H^3	57.5	0.2	Zn^{65}	4.2×10^{-3}	6×10^{-2}
C^{14}	99.9	3×10^{-3}	Sr^{89}	10^{-18}	7×10^{-5}
Na^{24}	10^{-1768}	8×10^{-3}	Sr^{90}	75.8	8×10^{-7}
P^{32}	10^{-75}	2×10^{-4}	Y^{91}	10^{-17}	0.2
S^{35}	10^{-8}	5×10^{-3}	Zr^{95}	10^{-17}	
K^{42}	10-1998	1×10^{-2}	Ru^{103}	10^{-25}	
Ca^{45}	10^{-5}	5×10^{-4}	Ru^{106}	0.1	0.1
Cr^{51}	10^{-39}	0.5	I^{131}	10^{-136}	3×10^{-5}
Fe^{55}	9.3		Cs^{137}	81	1.5×10^{-3}
Fe^{59}	10^{-22}	4×10^{-3}	Ce^{141}	10^{-32}	
Co^{60}	26.5	2×10^{-2}	Ce^{144}	1.3×10^{-2}	4×10^{-2}
Cu^{64}	10^{-2026}	1×10^{-4}	Pm^{147}	6.2	1

MPC for mixtures of isotopes of unknown composition is 10^{-7} uc/ml.

The practice of mixing contaminated materials into concrete which is then cast into the steel drum, provides for containment beyond the life of the steel drum. On the other hand, experiments designed to test the effect of hydrostatic pressure on disposal containers, indicated that voids in concrete may, at depths of a few hundred to a thousand meters, permit implosion of the steel drum and fracture of the concrete, thereby bringing about premature release of contaminant to the sea.

The tests of canisters which have been performed have been concerned with disposal into at least 1000 fathoms of water where pressures in excess of 3000 pounds per square inch will be encountered, whereas we are concerned here with water depths up to approximately 30 fathoms where pressure less than 100 pounds per square inch will be encountered. Although there is some doubt as to whether presently used containers remain intact after disposal to the sea bottom, proper design and testing can provide the necessary information.

After release to the sea, following intentional introduction of liquid wastes or after rupture of a canister, the concentration of the waste will be continually diminished by dilution brought about by the natural turbulent mixing processes that occur in the sea, and the mixture of waste and sea water will be moved from the disposal site by ocean currents. An evaluation of the extent of dilution together with processes that might combine to return the wastes to man are discussed below.

TRANSPORT AND DISPERSION

The movement of a contaminant from the disposal area and its dilution with sea water will be controlled by circulation in and adjacent to the disposal site and the natural turbulent mixing processes in the sea. Obviously, the bottom water circulation in the immediate area of the disposal site will control the initial movements of the soluble and finely divided waste as it diffuses from the ruptured canister.

Movement of Bottom Sediment

The mechanisms and patterns of bottom sediment transportation on continental shelves are poorly understood. The general circulation of the near-bottom water does not wholly control the movements of bottom sediments since tides, waves, storm surges and tsunami impose controls which may in fact outweigh in importance the average circulation of near-bottom water. Important in such considerations is the recent conclusion independently proposed by several groups studying the sediment budget of North Sea beaches that up to half the sediments contributed to certain advancing beaches has been derived off shore from the floor of the North Sea. The possibility thus exists that detrital waste may reach adjacent beaches in undesirable quantities.

The base of effective wave action has been variously estimated at 30 feet to 900 feet. The discovery of strong scour on seamounts and on the Mid-Atlantic Ridge to depths of 2000 fathoms has been interpreted as evidence that there is no effective wave base. On the other hand, most geologists believe that really intense wave action is limited to the upper 30 to 100 feet of the ocean. Because movement of bottom materials can be quite independent of the average water circulation since it partly

depends on wave action and not wholly on water transport, it must be considered separately. Before extensive inshore dumping is commenced, it would seem desirable to dump harmless trace material and observe from what distances appreciable material reaches the adjacent beaches.

Near-bottom Water Circulation

Sub-surface circulation has not been studied with sufficient detail to provide a basis for reliable prediction of the direction and speed of transport at all seasons of the year in any location that might be chosen for a disposal area. Evaluation of bottom circulation must be inferred from observations of salinity and temperature distributions, and measurements of surface drift, the latter largely from drift bottle experiments. A few direct measurements of bottom currents have been made from lightships.

Our knowledge of bottom water circulation along the Atlantic Coast may best be summarized by the following four items:-

a. There is an area extending from south of Nantucket Shoals westward to the offing of New York from about 30 fathoms to 50 fathoms which appears to be somewhat isolated from the general circulation pattern. Following the vernal development of the pycnocline this lens of water retains its winter characteristics, remains in the same geographic location and does not become modified until the autumn overturn. There appears to be restricted interchange of some of the water seaward with slope water. In other words this portion of the

continental shelf below the pycnocline tends to stagnate for about six months of the year.

b. Observation posts on lightships reveal a mid-summer inshore movement of bottom water along the coast from Virginia to New Jersey and subsequent upwelling, presumably due to offshore movement of surface waters due to wind shear. How far inshore from the lightships this intrusion occurs we do not know.

The observations also suggest a downwelling during the coldest parts of the winter when waters next to the coast chill to low temperatures, and subsequent offshore movement when resulting densities reach below those of the adjacent offshore waters. This mechanism appears to occur in areas farthest from river mouths where the salinity inshore is highest. This phenomenon has been observed at Nantucket Shoals where the bottom offshore movement was deduced to reach 2 miles per day (4 cm/sec) and south of Long Island where chilled coastal water contributed to the offshore lens of cold water.

c. The pycnocline develops only very weakly in the coastal areas south of Cape Hatteras, allowing greater vertical mixing here than to the north where the pyncnocline is better developed.

d. Bottom flow in the areas seaward from the mouths of estuaries can be expected to be shoreward, with intensification of shoreward movement during seasons in which the land drainage into the estuary is at a maximum.

Surface circulation.

The movement of surface waters, summarized below, will be important to the distribution of contaminant after diffusion and transport from the bottom have brought the contaminant into the surface waters.

a. At the seaward end of all coastal estuaries the surface flow can be expected to be seaward with a tendency toward southerly flow along the coast adjacent to the estuary.

b. In general the circulation in the Gulf of Maine comprises a counterclockwise eddy. The drift along the Maine-Massachusetts coast is southerly, on the order of 2-6 miles per day (4-13 cm/sec). The southerly part of the circulation, in Massachusetts Bay, is comprised of two drifts, one counterclockwise around Cape Cod Bay, and one across the mouth of Massachusetts Bay toward the outer coast of Cape Cod and thence southerly. The drift from Georges Bank is generally west during the spring and summer but more offshore and perhaps even easterly during the autumn and winter.

c. South of Massachusetts, Rhode Island,and New York the coastal drift tends to be westerly, 3-5 miles per day, (6-11 cm/sec) and from the offing of New Jersey southward to Cape Hatteras the set is southerly with speeds varying from 3-15 miles per day (11-32 cm/sec).

d. From Cape Hatteras to Georgia the surface non-tidal drift tends northeasterly at speeds of 0.2 to 12 miles per day, (.4 to 26 cm/sec) with the highest concentrations of drift bottle strandings on the southern side of the Capes. From Georgia to

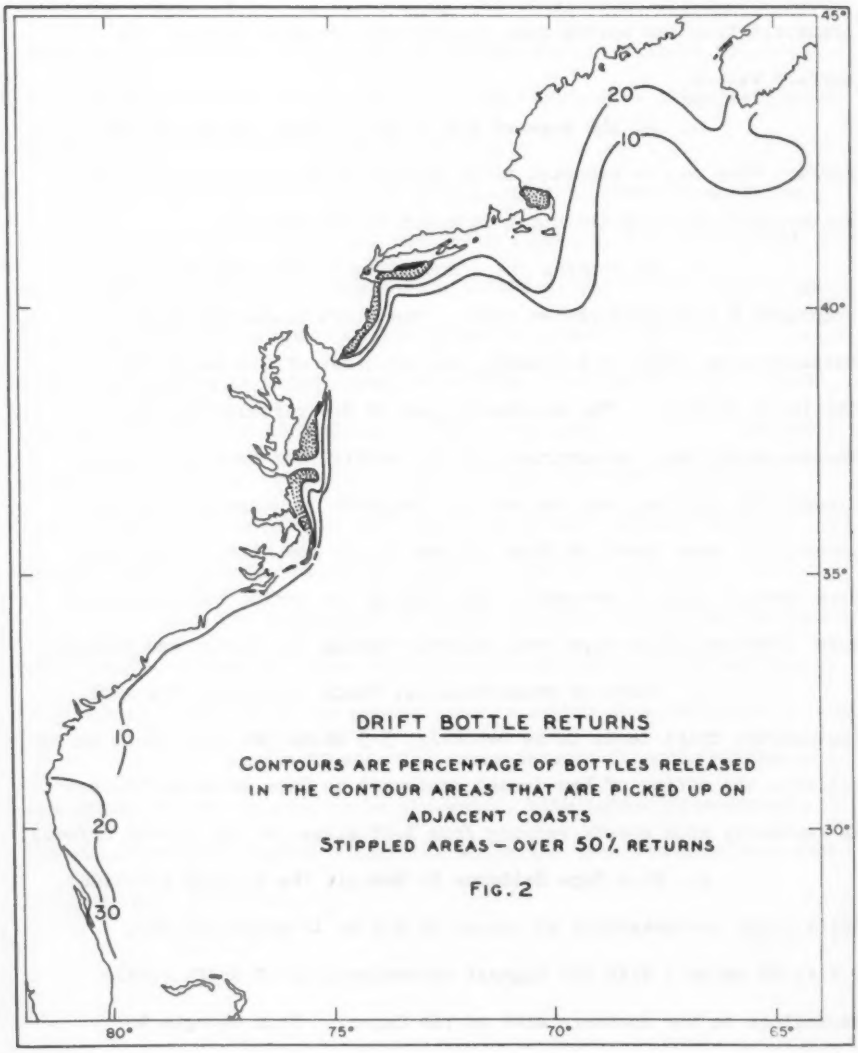
45°
40°
35°
30°
80°
75°
70°
65°
20
10
10
20
30
DRIFT BOTTLE RETURNS
CONTOURS ARE PERCENTAGE OF BOTTLES RELEASED IN THE CONTOUR AREAS THAT ARE PICKED UP ON ADJACENT COASTS
STIPPLED AREAS – OVER 50% RETURNS

FIG. 2

Daytona Beach the set appears to be southerly and from Daytona Beach south the drift appears to be northerly (unpublished data).

e. Redfield and Walford (11) noted that "..wastes likely to be transported to beaches in the surface layers should be carried at least 10 miles to sea if contamination of beaches is to be avoided." The percentage frequency of strandings of drift bottles from areas off the U.S. coast, figure 2, indicates the variation in what may be construed as onshore or offshore areas of drift. The contours extend farthest offshore in the Gulf of Maine and south of Nantucket. They bend in towards the mouths of the Hudson River, Delaware and Chesapeake Bays. On the other hand, on either side of the mouths of these estuaries the frequency of returns is high. Note also the high percentage of returns from bottles dropped from Georgia southward.

Diffusion Processes

In addition to the gross transportation of contaminants by permanent and semi-permanent ocean currents, the mechanism by which a contaminant will move from the bottom if current velocities are zero at the water-bottom interface is obviously important. This mechanism is diffusion controlled. Similarly, once the contaminant is contained in water its dispersion and subsequent dilution will also be controlled by turbulent diffusion processes. So far as can be discovered, there are no direct measurements of diffusion-controlled processes within the areas of interest that can be used to evaluate the relative importance of these mechanisms to the movement of the

contaminants. It is possible, however, to treat the problem theoretically, by imposing a number of simplifying assumptions which give a result that is not an accurate description of the diffusion process, but does give limiting values of the concentration of contaminant in the sea. Reid (12) has examined several cases in which the following assumptions were made:

a. The radioactivity in sea water is not depleted by adsorption by the bottom solids, or by the uptake of marine organisms.

b. Natural radioactive decay has been neglected.

c. The diffusion process is considered to be Fickian.

d. The ocean is considered to be of uniform depth.

The assumption of Fickian diffusion implies that the dispersion of a contaminant at distances from the source is much slower than is known to occur. The assumptions of no adsorption by bottom solids and marine organisms, and no radioactive decay obviously lead to an overestimate of the concentration of contaminant.

Several cases are considered, corresponding to possible conditions of release of the contaminant to the sea. These are summarized below.

Sustained Gross Source. This case is analogous to the continued release of a contaminant, at a known rate, as from the end of a pipe, or the diffusion of contaminant from ruptured canisters, under a steady state condition of supply and rupturing of canisters.

Considering a bottom disposal area of dimension L x L, over which the water depth is D, with a uniform current of speed U

parallel to the coast, and a diffusivity coefficient K, the maximum concentration of contaminant Cm along the axis of the current at distance x from the source, (when x is large compared with L) for a rate of supply Q, is given by:-

(1) $$C_m = \frac{Q}{2D\sqrt{2\pi K u x}}$$

The maximum concentration at various distances as evaluated from equation (1) are listed in Table IV for the following conditions:

Rate of supply Q = 100 curies per year (274 mc/day)

Depth of water D = 30 meters (90 feet)

Diffusivity coefficient K = 1 cm^2/sec

Current velocity U - 10 cm/sec (approx. 5 n.mi/day)

TABLE IV

Maximum concentration C_m at distances x from sustained gross source with rate of supply 100 curies per year.

x (Km)	C_m (μc/ml)
1	2×10^{-7}
2	1.6×10^{-7}
4	1×10^{-7}
10	7×10^{-8}
20	5×10^{-8}
40	3×10^{-8}
100	2×10^{-8}

It has been estimated that because of the assumptions under which equation 1 was developed, the concentrations listed in Table IV

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are certainly high by at least a factor of 10, and probably by a factor of 100.

Instantaneous Source. This case is analogous to the sudden rupturing of a cubical canister on the bottom under the assumption that all of the contaminant is then free. Assuming no current to aid in dispersal, the reduction in concentration at the canister due to diffusion processes is given by:-

$$C = \frac{C_o}{4} \frac{V}{(\pi K t)^{3/2}}$$

where, C = the concentration at time t

C_o = initial concentration

V = volume of canister

K = diffusivity coefficient

The ratio of the interim concentration to initial concentration as a function of time for the specific case of K = 1 cm^2/sec, V = 190 liters (volume approx. 50 gallons) is given in figure 3. It is seen that 0.01 curies contained initially in approximately 50 gallons, Co = 54 μc/kg, would be reduced to approximately 2 μc/kg in 1 hour and to 0.06 μc/kg in 10 hours.

In addition to the time-concentration relationship, it is of interest to know the effect of distance from disposal site on the concentration for point sources. The maximum relative concentration (C/Co) as a function of distance from the site is shown for three cases in figure 4. Curve 1 assumes infinite depth of water, curve 2 assumes that the ratio of water depth to canister size is 100, and curve 3

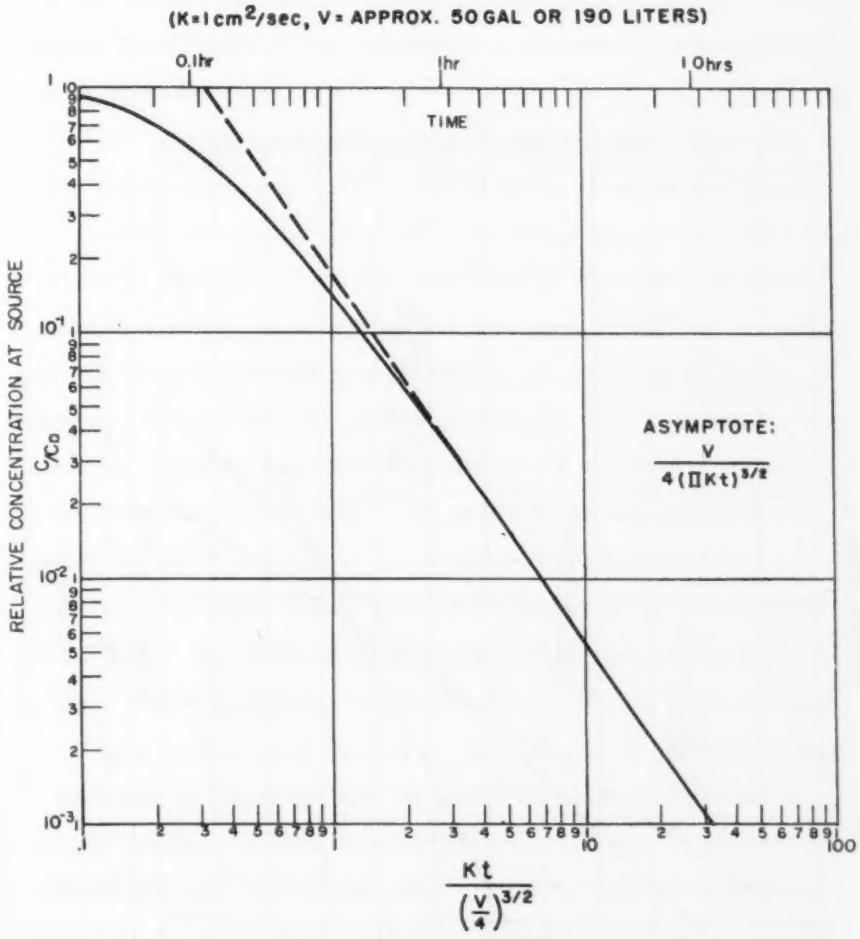


FIGURE 3

DIFFUSIVE DECAY OF CONCENTRATION AT SOURCE
SOURCE ON BOTTOM
D = ∞

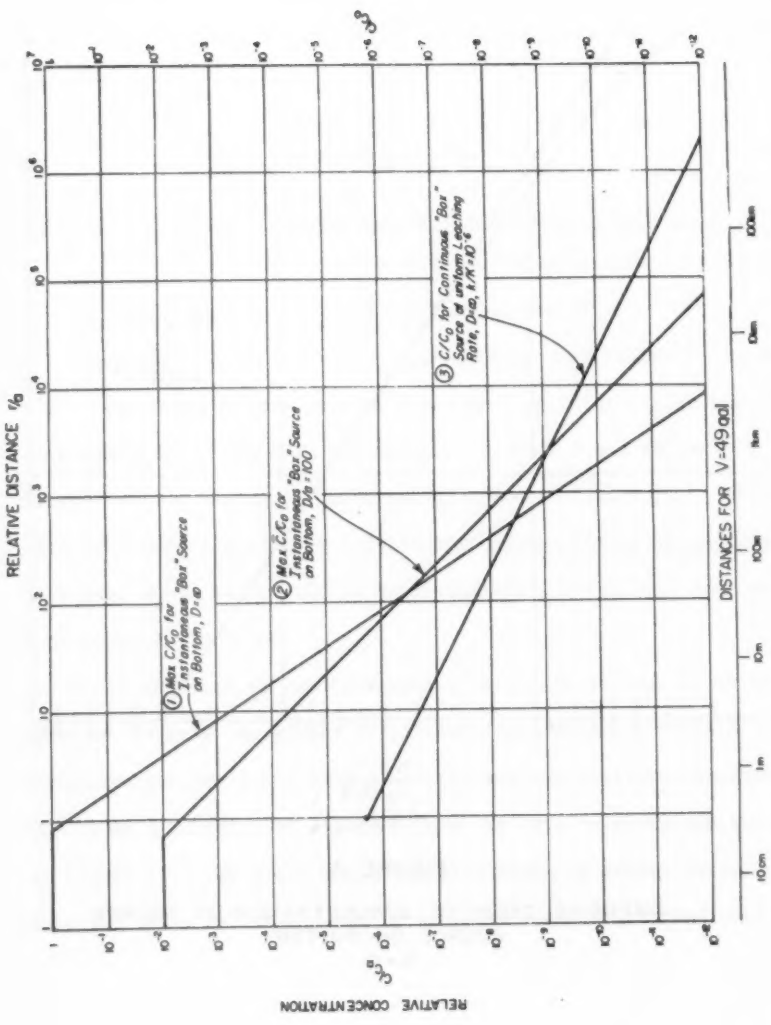

RELATIVE DISTANCE r/r0
RELATIVE CONCENTRATION C/C0
DISTANCES FOR V=49 cd
(1) Max C/C0 for Instantaneous "Box" Source on Bottom, D=0
(2) Max C/C0 for Instantaneous "Box" Source on Bottom, D/a=100
(3) C/C0 for Continuous "Box" Source at uniform Leaching Rate, D=0, t/T=10^-6

FIGURE 4

RELATIVE CONCENTRATION VERSUS DISTANCE FROM SOURCE

assumes infinite depth and that all of the waste is not immediately available but diffuses from the ruptured canister at a uniform rate under the conditions that the diffusion coefficient through the ruptured canister is 10^{-6} that of the diffusivity in the water. The latter case is discussed below.

Continuous Source at Uniform Leaching Rate. This case treats the situation analogous to the diffusion of contaminant from the concrete that remains after the steel casing has corroded and affords no further containment. In the development of this case, it has been assumed that the amount of contaminant diffusing through the permeable concrete walls is directly proportional to the surface area of the container, directly proportional to the difference in concentrations inside and immediately outside the container, and inversely proportional to the thickness of the walls. The effective diffusion coefficient through the walls is taken as the molecular diffusivity times the porosity of the walls, and in numerical computations is assumed to be 10^{-6} cm^2/sec. The relative concentration-distance relationship is shown by curve 3 in figure 4.

Reid further shows that under the condition of continual supply of canisters to a disposal area and given the assumptions noted above, the time required to reach a steady state between rate of disposal and leaching rate will be fourteen years. That is, only after fourteen years will the quantity of contaminant released to the water be equal to the rate at which contaminant is deposited on the bottom in canisters.

If the life of the steel canister is ten years, as noted previously, the time to reach steady state would then be an additional ten years, or a total of twenty-four years.

SORPTION AND EXCHANGE

Coastal waters in general contain relatively large quantities of suspended solids. The solids are in part living organic materials, the plankton, and in part suspended, inanimate, organic and inorganic solids. A portion of the latter are materials being carried seaward by land drainage sources and will ultimately become bottom deposits. Another portion, that usually near the ocean bottom, is periodically brought into suspension by tidal action and storm-generated turbulence. All these materials including the "bottom" have a measurable tendency to adsorb (remove from solution) and to hold substances dissolved in the water.

The sorptive properties of these solids are extremely variable. Neglecting for the moment uptake by marine organisms, the quantity of material adsorbed by a given weight of suspended inorganic solids will depend upon the mineral composition of the solids, the composition of the solution in which the solids are suspended, and the past history of the solids. All of these factors are nearly impossible to evaluate quantitatively for conditions likely to be found in nature.

Although impossible to evaluate quantitatively, it seems certain that sorption processes will play a major role in controlling the dispersal of radioactive wastes once they are free of the canister. This conclusion is based upon the results of a few laboratory studies, in

addition to qualitative field observations made during bomb tests and by the British at their disposal operation in the Irish Sea. The details are given in NAS-NRC publication 551, chapter 6 (5), and are summarized below:

1. Partial removal of mixed fission products from solution was achieved by centrifugal separation of naturally occurring solids from a contaminated solution.

2. The sorption of phosphate, iodide, iron III, strontium, sulphate, and copper II onto Chesapeake Bay sediments has been measured under a variety of environmental conditions. With the exception of iodide, appreciable removal from solution by the solids was observed under all conditions.

3. Sorption onto selected clay minerals has been studied and is recommended as a means of solution decontamination, under certain conditions.

4. The differences in composition between marine sediments and the solids carried to sea by rivers is attributed to exchange and sorption reactions between the solids and dissolved substances during sedimentation.

5. The sediments in the area around the end of the discharge line from the British Atomic Energy Authority processing plant at Windscale on the shore of the Irish Sea, show a relatively large accumulation of radioactive substances.

Although some of this information is quantitative it cannot be applied directly to the dispersal problem we are considering. Nevertheless,

considering that exchange and sorption reactions appear to be a more or less general behavior exhibited by radioactive waste components and naturally occurring suspended and deposited solids, and realizing that the disposal canisters will be partially or perhaps completely buried in bottom deposits during the time the waste components are escaping from them, it seems inevitable that these reactions will have a major influence in controlling the rate of dispersal and ultimate distribution of the wastes.

These sorption and exchange reactions appear to us to be a safety factor (an exception is noted below) in disposal problems. So far as uptake by permanent bottom deposits are concerned the effect is that of achieving additional containment time, thus providing for greater radioactive decay than would be achieved by containment only in the canister.

There is at least one situation in which sorption onto bottom deposits may represent the development of a possibly hazardous situation. This is the situation in which bottom areas adjacent to a disposal site are the source of marine food products such as oysters, clams, mussels, etc. In this case accumulation of wastes on the bottom would provide for a greater level of contamination of the food product than would occur in the absence of sorption and exchange with the bottom. Our recommendation of a complete survey of a proposed inshore disposal area prior to the start of disposal operation will help preclude the development of such a hazard.

Because we are unable to make a quantitative estimate of the

magnitude of uptake on suspended and deposited solids, we have neglected this factor in our evaluation of the quantities of wastes likely to be found in the water and in marine food products for various rates of disposal of radioactive wastes. We believe that by neglecting this factor our recommendations concerning disposal rates include a safety factor of at least 10, and possibly more.

PERMISSIBLE CONCENTRATIONS OF RADIOISOTOPES IN SEA WATER AND UPTAKE BY MARINE ORGANISMS.

We have noted previously that we consider the return of radioactive wastes to man in the form of contaminated marine food products to be the most serious potential hazard that might be created by the use of near-shore areas as disposal sites.

The ability of aquatic organisms to concentrate certain substances within themselves at higher levels than exists in their environment is well known. From earlier studies involving the concentration of the major nutrients, carbon, nitrogen, and phosphorus by phytoplankton, the aquatic plants, and the passage of these materials from plants to animals through successive prey - predator steps, we have a generalized picture of the nutrient cycles in which many kinds of aquatic organisms are involved. Following these early studies with the major nutrients, several of the trace metals that appear as minor but essential nutrients were studied, and recently the behavior of radioisotopes of several biologically important elements has become known. This information was discussed in detail in NAS-NRC publication 551, chapters 7, 8, and 9 (5). Using this information, plus the

results of studies completed since 1957, we can estimate the quantities of many radionuclides that will be contained within a variety of aquatic organisms when their environment contains stated concentration of the same nuclides.

We have combined this information regarding the probable quantities of radionuclides in commercially landed fish with figures for maximum permissible concentrations in drinking water, to obtain the quantity of radionuclids that will be returned to man in marine food products, as follows:

1. The MPC values (3) are based upon acquiring a permissible body burden of a given radionuclide, below which no observable biological damage will occur, by drinking approximately 15,000 milliliters (15 liters) of water per week, at MPC levels, for 30 years. Thus, the MPC values permit the calculation of a permissible weekly intake for each of the nuclides listed. For example, the MPC value for Sr^{90} is 8×10^{-7} $\mu c/ml$. We calculate the permissible weekly intake of Sr^{90} to be 1.2×10^{-2} μc.

2. Using the permissible weekly intake as calculated above and figures for the quantity of fish eaten per person per week, it should be possible to compute the maximum permissible concentration of any nuclide in fish.

In contrast to the drinking of water, man's seafood eating habits are extremely variable. According to Taylor (13) the average U.S. consumption of seafood is approximately 10 pounds per year. Comparable figures for other countries are France, 20; Great Britain, 48;

Japan, 111 pounds per year. The average consumption of seafood, however, has little significance since large proportions of the population live far from the sea coast and eat little or no fish or other marine products. A man would have to eat approximately four pounds of fish weekly in order to match the average U.S. protein consumption. It has seemed to us reasonable to take a value approaching this as the extreme case of an individual subsisting almost entirely on fish as the source of protein in his diet, and have used 1.5 kg (3.3 pounds) per week in further computations. For example, for Sr^{90}, using $1.2 \times 10^{-2} \mu c$, computed above, as the maximum permissible weekly intake of nuclide and 1.5 kg as the weekly consumption of fish, we compute $8 \times 10^{-3} \mu c/kg$ as the maximum permissible concentration of Sr^{90} in fish.

3. Next, having the maximum permissible concentration of a nuclide in fish and the concentration factor achieved by fish for the nuclide we compute the maximum permissible concentration for the nuclide in sea water. Again using Sr^{90} as an example, the maximum permissible concentration in fish of $8 \times 10^{-3} \mu c/kg$, combines with a concentration factor of 10, assuming the density of fish to be 1.0, to give a maximum permissible concentration in sea water of $8 \times 10^{-4} \mu c/liter$ or $8 \times 10^{-7} \mu c/ml$, which by coincidence is identical with the MPC value in drinking water.

4. These computations are summarized by the relationship:

$$MPC \times D = PSC \times f \times F$$

where:

MPC = maximum permissible concentration in drinking water (μc/ml)

D = volume of water drunk per week, taken as 15,000 ml

PSC = permissible sea water concentration (μc/ml)

f = concentration factor by the organism

F = weekly consumption of fish, taken to be 1.5 kg, and assuming a density of 1.0, to be equivalent to 1,500 ml.

Computations, outlined above, have been made for a number of radionuclides, including the major isotopes shipped from ORNL, as well as several of the more hazardous fusion product elements. These computations are summarized in Table V.

TABLE V

SUMMARY OF PERMISSIBLE CONCENTRATION OF SELECTED RADIONUCLIDES IN DRINKING WATER; EDIBLE MARINE PRODUCTS; AND SEA WATER.

	1. MPC (μc/cc)	2. Maximum weekly dose (μc)	3. PFC (μc/gm)	4. Concentration factor	5. PSC (μc/ml)
H3	0.2	3.000	2	-	-
C14	3×10^{-3}	45	3×10^{-2}	-	-
Na24	8×10^{-3}	120	8×10^{-2}	0.5	1.6×10^{-1}
P32	2×10^{-4}	3	2×10^{-3}	4×10^{4}	5×10^{-8}
S35	5×10^{-3}	75	5×10^{-2}	5	1×10^{-2}
K42	1×10^{-2}	150	1×10^{-1}	10	1×10^{-2}
Ca45	5×10^{-4}	7.5	5×10^{-3}	10	5×10^{-4}
Cr51	5×10^{-2}	750	5×10^{-1}	-	-
Fe59	4×10^{-3}	60	4×10^{-2}	10^{4}	4×10^{-6}
Co60	2×10^{-2}	300	2×10^{-1}	10^{4}*	2×10^{-5}
Cu64	8×10^{-2}	1200	8×10^{-1}	5×10^{3}	1.6×10^{-4}
Zn65	6×10^{-2}	900	6×10^{-1}	5×10^{3}	1.2×10^{-4}
Sr90	8×10^{-7}	0.012	8×10^{-6}	10	8×10^{-7}
I131	3×10^{-5}	0.45	3×10^{-4}	100	3×10^{-6}
Cs137	1.5×10^{-3}	22.5	1.5×10^{-2}	50**	3×10^{-4}
Ir192	9×10^{-4}	13.5	9×10^{-3}	-	-

1. Handbook 52 values (3)

2. From MPC and weekly ingestion rate of 15 liters of water.

3. Permissible fish concentration. From maximum weekly dose, and weekly ingestion rate of 1.5 kg of fish.

4. The concentration factors for the soft tissues of vertebrates or invertebrates, whichever is higher, from Revelle and Schaeffer (5). In all cases, except P32, figures are for invertebrates; vertebrates are lower by a factor of one half to one tenth.

* maximum factor for plankton species. Ketchum and Bowen (in press).

** data for soft tissues of oysters. Chipman (unpublished).

POSSIBLE CONFLICT WITH OTHER INTERESTS

Commercial Fisheries

Many areas along the Atlantic and Gulf coasts of the United States have well developed, active fisheries. The disposal of radioactive wastes in these areas might be objectionable, not only because of the possibility of contamination of the fish, with the development of a potential hazard to consumers, but also because the accumulation of disposal containers on the bottom might create a hazard to fishing equipment, especially to trawl gear that would become damaged or possibly lost if dragged over heavy concrete disposal containers. Furthermore, if radioactive disposal areas are to be closed to fishing, as they undoubtedly should be, it is in the interest of the best uses of our marine resources that disposal areas be placed where little or no fishing now occurs.

In some areas the fishing intensity is well defined. This is the case in the coastal area northward from Long Island and including the Gulf of Maine. Most coastal estuaries have well developed

fisheries. Thus, such areas as Delaware Bay, Chesapeake Bay, Albemarle Sound and Pamlico Sound are undesirable locations for disposal sites not only because of the shoreward transport in the bays and the restricted circulation in the sounds, but also because of possible conflict with the fisheries.

The region east and slightly south of Long Island between the 30 and 50 fathom contours, in which fishing vessels are unlikely to be found, conicides with the region noted previously to be characterized by "summer stagnation". The lack of fishing effort in this area suggests it as a possible location for disposal sites. However, the restricted circulation through the region for about six months of the year suggests that during the times of "stagnation" an accumulation of wastes might occur in the area to such an extent that adjoining areas might be adversely affected once circulation is restored following the fall turn-over. At best, regions of this kind should be used as disposal sites only after a careful study of the year round exchange of water with adjoining areas.

Unfortunately, detailed studies have not been made over the entire Atlantic and Gulf coasts. However, it seems likely that appropriate information can be obtained, for any proposed site, from state and local fisheries groups.

In general the trend is toward the development of fisheries in deeper and deeper water. At present very little fishing is done beyond 100 fathoms. However, experimental fishing has been carried on out to 1000 fathoms, and indications are that with an increased demand for fish

and with the development of the proper fishing gear, these relatively deep areas can support a considerable fishing effort.

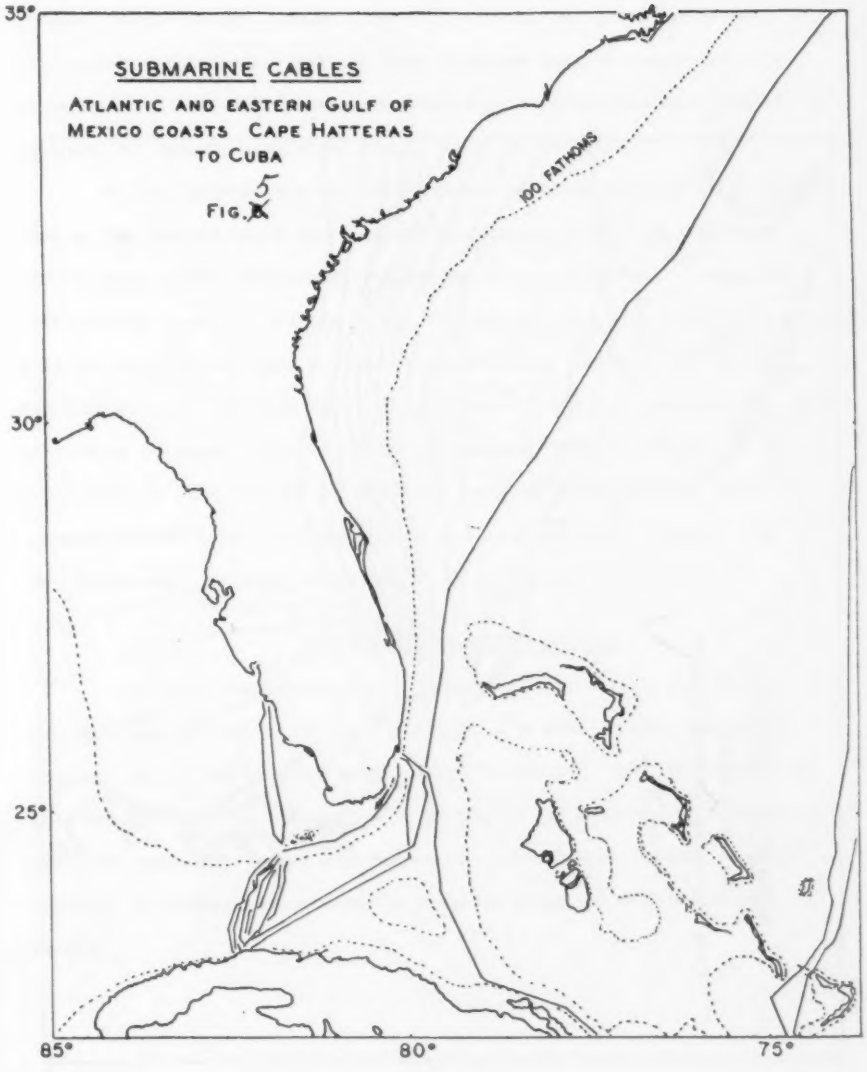
Submarine Cables.

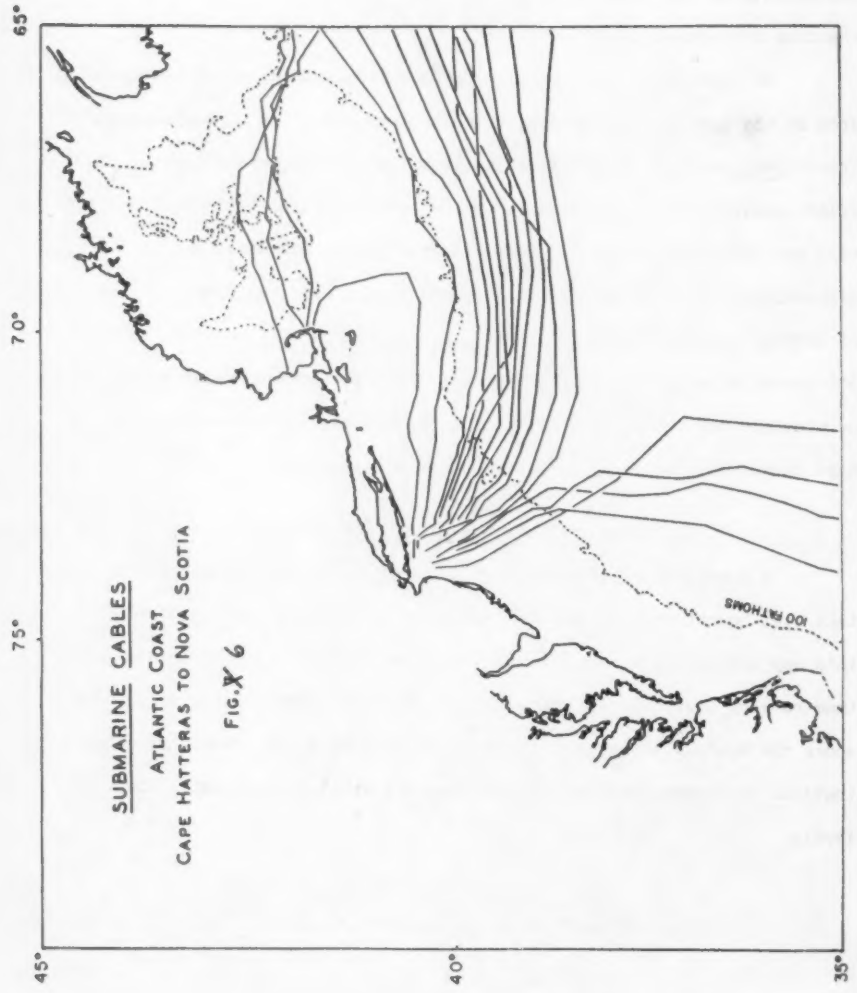
The disposal of packaged radioactive wastes in areas through which submarine cables pass will be objectionable from two points of view. First, there is a possibility of damage to the cable should a disposal container fall directly on it during disposal operations. Second, during cable maintainance and repair it is common practice to drag grappling equipment across the ocean bottom to locate the cable and to bring it to the surface. An accumulation of disposal containers on the bottom in such a location not only could interfer with the grappling operation but might result in the premature rupture of a disposal container with possible exposure of personnel to measurable radiation.

The location of submarine cables along the east coast of the United States is shown in figures 5 and 6. Proposed disposal sites have been chosen in areas not crossed by cables.

MAXIMUM RATE OF DISPOSAL

The maximum rate of disposal should be such that permissible sea water concentrations are not continuously exceeded. Several problems arise when this criterion is applied to practical disposal operations. Firstly, disposal is a discontinuous process and even though activity will probably slowly leach from disposal containers for quite some time following rupture of the canister, it is highly unlikely that the rate of supply of activity to the water will be constant. How then should we average such a process? Secondly, the flux of contaminant from a disposal container


SUBMARINE CABLES
ATLANTIC AND EASTERN GULF OF MEXICO COASTS CAPE HATTERAS TO CUBA
FIG. 5
100 FATHOMS
35°
30°
25°
85°
80°
75°


65°
70°
75°
45°
40°
35°
100 FATHOMS
SUBMARINE CABLES
ATLANTIC COAST
CAPE HATTERAS TO NOVA SCOTIA
FIG. X 6

will decrease as the amount of contaminant in the container decreases, producing an effect similar to that noted above. Thirdly, only a small fraction of the total volume of coastal waters will actually pass directly over a disposal area, however, a much larger fraction of the total volume will be available for dilution. Most of these problems involve the averaging of concentrations that will be above and below permissible sea water concentrations for unknown lengths of time.

We have solved this problem by using the boundaries of the disposal area as the spatial limit beyond which the concentration of contaminant should never exceed the permissible sea water concentration. Using the relationship shown in equation 1, (p. 32) and assuming that a disposal canister will not contain more than 2 curies (approximately the limit set by ICC regulations), we find that for a disposal area 2 miles in diameter (the size of several suggested disposal areas), a disposal rate of between 200 and 300 curies of strontium 90 per year will keep the concentration below the permissible sea water concentration at the disposal area boundry. We have chosen 250 curies of strontium 90 or its equivalent.

PRE-USE SURVEY AND MONITORING

A precise evaluation of the quantity of radioactive substances that will be returned to man as the result of a stated rate of disposal into any one of the selected areas cannot be given. The recommended maximum rate of disposal (250 curies of Sr 90, or its equivalent) will, even under the most unfavorable combination of circumstances, result in concentrations of contaminant outside the disposal areas below permissible levels.

In order to obtain essential information not now available that will permit full utilization of the disposal areas without limiting other uses of coastal waters, the committee recommends, (1) a survey of any area prior to disposal operations, and (2) the monitoring of an area subsequent to the beginning of disposal operations.

The pre-use survey should be designed to provide the following information:

1) Detailed circulation, including seasonal variations, in and adjacent to the disposal area, conducted so as to permit an evaluation of the dilution afforded by turbulent mixing within the area and transport from the area by ocean currents.

2) Measurement of the seasonal variations in the kind and quantities of aquatic organisms within and adjacent to a disposal area, especially organisms attached to or living in the bottom, These may concentrate or move components of the wastes and so act first as a containment element and second as a convenient indicator, during subsequent monitoring operations, of the spread of activity throughout the disposal area and of possible "leaking" out of the disposal area.

3) Analysis of bottom sediments for mineral types, especially for components known to have high absorptive capacities, e.g. the clays.

4) Analysis of bottom organisms and bottom deposits for existing radioactivity. This will be low prior to disposal, being primarily from natural activities and fall-out. The analysis should be conducted so as to distinguish between naturally occuring K^{40} and C^{14} and man-made isotopes, especially Sr^{90}.

5) The existence of commercial and sports fishing activities within and adjacent to the selected area, determined by reference to U.S Fish and Wildlife records and state and local authorities.

Monitoring of a disposal area at intervals following the start of disposal operations will be essential to the safe and efficient use of an area. Monitoring procedures should include the collection of both bottom living organisms and bottom sediments, and analysis of each for radioactivity. The frequency of sampling and the methods of analysis should be such that estimates of the following can be made:

1) Containment provided by disposal canisters;

2) the distribution of waste components in the biota and the bottom sediments;

3) the existence of a steady state involving disposal rate and distribution within the disposal area.

DISPOSAL AREAS

Suggested disposal areas are shown in figure 7, and their exact location listed in Table VI.

Inasmuch as there are a number of disposal areas presently available, designated as "explosives dumping area" or "dumping ground (by permit only)", some of which have been used heretofore for the disposal of low level radioactive wastes as well as for certain toxic chemical wastes, we have included these areas in the list of suggested sites. We have numbered the sites 1 to 12. Alternative sites have been marked with the subscript a or b indicating that they might be used as secondary disposal areas but are more inconvenient to reach than the primary disposal area.

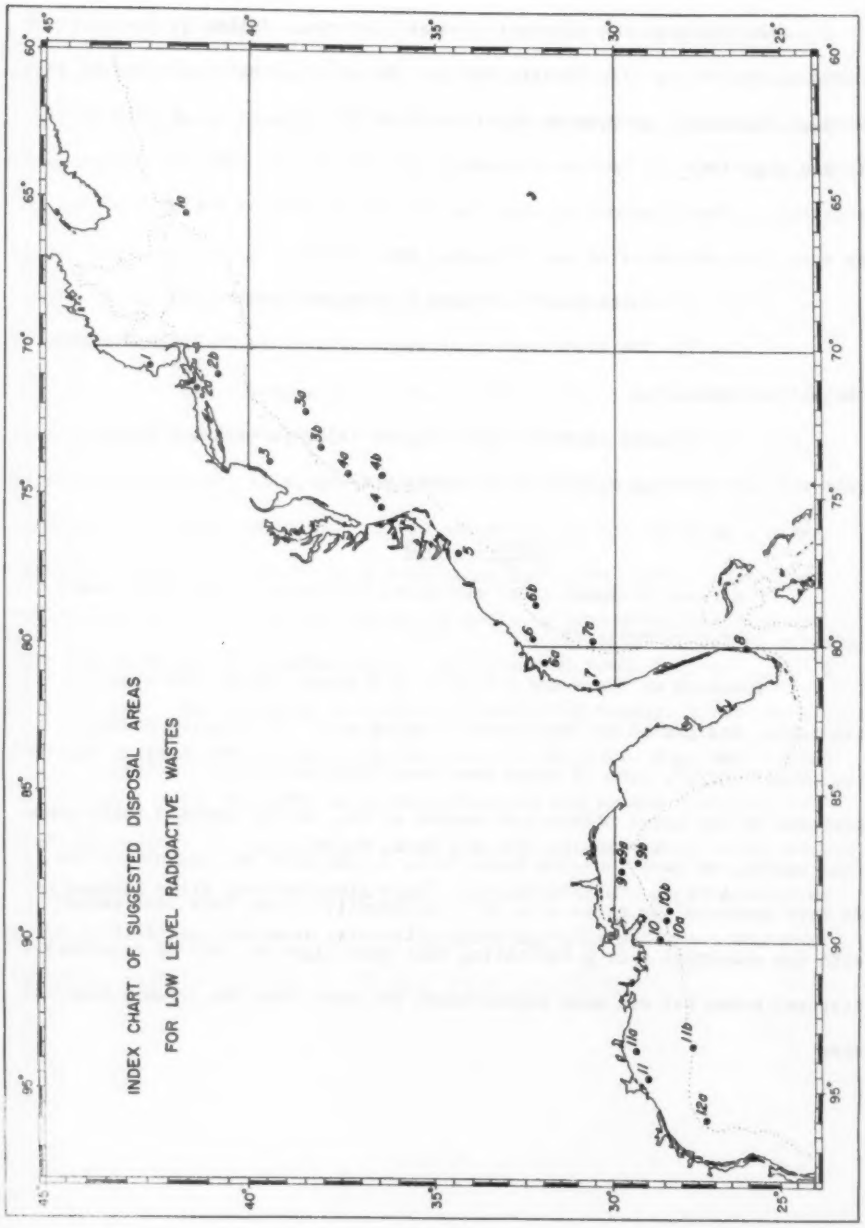

INDEX CHART OF SUGGESTED DISPOSAL AREAS
FOR LOW LEVEL RADIOACTIVE WASTES
60°
65°
70°
75°
80°
85°
90°
95°
45°
40°
35°
30°
25°

FIGURE 7

Most of the dumping areas are large: 10 x 10 miles, 10 miles in diameter, or the like. We have indicated the centers of these areas, with one exception. Additional sites listed might be two miles in diameter centered on the positions given. Sites presently listed in "A special report on disposal of radioactivity into Atlantic Ocean waters-past, present, and predicted", U.S.A.E.C. Division of Reactor Development, November 1957, are marked with an *.

TABLE VI

LOCATION OF SUGGESTED DISPOSAL AREAS

To serve Boston, Massachusetts:

1* 42°25.5'N 70°35'W 312' 2 miles in diameter, marked "Foul Area, Explosives" presently used by Crossroads Marine Disposal Company, 22 miles from Boston, Chart 1207

1a* 41°33'N 65°30'W 1000 fm. "Explosives Dumping Area" 10 x 10 miles square, Chart 71

To serve Providence, Rhode Island:

2 41°19.7'N 71°063'W 48-90' Rocky ledge known as "Browns Ledge" 10 miles from Sakonnet, Rhode Island, Chart 1210

2a 41°14'N 71°25'W 110-126' 2 miles in diameter marked "Danger, Unexploded Depth Charges, May 1952", 10 miles from Pt. Judith, Rhode Island, Chart 1210

2b 40°45'N 70°52'W 32 fm. "Explosives Dumping Area, Disused". 10 x 10 miles square, 45 miles from Sakonnet Point, Rhode Island, Chart 71,1108

FIGURE 7

To serve New York - Delaware Bay:

3. 39°26.7'N 73°56.6'W 80' "Danger Area" 2 miles in diameter 22.5 miles from Atlantic City, Chart 1217

3a* 38°30'N 72°06'W 1200-1500 fms. "Explosives Dumping Area" 10 x 10 miles square, 118 miles 098°T from Five Fathom Bank Lightship, Chart 1000

3b 38°05'N 73°24'W 930-1060 fms. "Explosives Dumping Area" 10 x 10 miles square, 70 miles 127°T from Five Fathom Bank Lightship, Chart 1109

To serve Norfolk, Virginia:

4 36°49'N 75°27'W Wreck 9-1/4 in 11 fm. 37 miles from Little Creek, Chart 1109

4a 37°19'N 74°15' W 500-800 fm. "Explosives Dumping Area" 10 x 10 miles square, 73 miles 074°T from Chesapeake Lightship, Chart 1109

4b* 36°30'N 74°18'W 1000-1250 fm. "Explosives Dumping Area" 10 x 10 miles square, 74 miles 113°T from Chesapeake Lightship, Chart 1109

To serve Morehead City - Beaufort, North Carolina:

5 34°26'N 76°54'W 77-81'. A "tear up" area according to "Report of North Carolina Shrimp Survey", Institute of Fisheries Research University North Carolina, January 1951. 22 miles from Morehead City, Chart 1234

To serve Savannah area:

6 32°20'N 79°55'W 10 fm. "Dumping Ground (by permit only)" 8.5 miles diameter, 20 miles 136°T from mouth of North Edisto R. Chart 1111

6a 32°00'N 80°30'W 60'. A poor bottom for fishing. 18 miles from Ft. Screven, Chart 1240

6b 32°15'N 78°40'W 20 fm. "Explosives Dumping Area", 10 miles diameter, 70 miles from Charleston, South Carolina, Chart 1111

To serve Jacksonville, Florida:

7 30°33'N 81°09.2'W 67-70' "Wreck, 42' Reported", 18 miles from Mayport, Chart 1243

7a 30°37'N 79°53'W 300 fm. "Explosives Dumping Area, Disused" 83 miles from Mayport, Chart 1111

To serve the Florida peninsula:

8 26°05.5'N 80°02.5' W 600 fm. 2 miles east of Port Everglades Sea Buoy, Chart 1248

To serve Pensacola - Mobile Bay:

9 29°48'N 87°33'W 23 fm. "Dumping Ground" 35 miles from Pensacola, Chart 1115

9a 29°48'N 87° 10'W 100 fm. Rough ground not suitable for trawling, 34 miles from Pensacola, Chart 1115

9b 29°22'N 87°15'W 300 fm. "Explosives Dumping Area, Disused" 10 x 10 miles square, Chart 1115

To serve New Orleans, Louisiana:

10 28°40'N 89°51'W 100 fm. Rough ground, not suitable for trawling, 26 miles from Southwest Pass, Chart 1116

10a 28°30'N 89°10'W 300 fm. "Explosives Dumping Area, Disused" 10 x 10 miles square, 30 miles from South Pass. Chart 1115

10b 28°25'N 88°55'W 600 fm. "Explosives Dumping Area" 10 x 10 miles square, 36 miles from South Pass, Chart 1115

To serve Galveston, Texas:

11 29°00'N 94°35'W 9 fm. Southernmost corner of a 5.5 x 11 mile rectangle. "Dumping Ground (by permit only)" 21 miles from Galveston Entrance, Chart 1116

11a 29°22'N 93°40'W 7 fm. Rectangular 4 x 9 miles "Dumping Ground (by permit only)" 19 miles from Sabine Pass, Chart 1116

11b 27°40'N 93°30'W 250 fm. "Explosives Dumping Area, Disused" 10 x 10 miles square, 100 miles 175°T from Galveston Entrance, Chart 1116

To serve Corpus Christi, Texas:

12a 27°15'N 96°00'W 250 fm. "Explosives Dumping Area, Disused" 10 x 10 miles square, 65 miles 122 °T from Aransas Pass, Chart 1117

REFERENCES

1. Anonymous. A Special Report on Disposal of Radioactivity Into Atlantic Ocean Waters. Past, Present, and Predicted. Division of Reactor Development, U.S. Atomic Energy Commission, Washington 25, D.C. November 1957

2. Anonymous. Packaging of Contaminated (Radioactive) Scrap for Disposal. U.S. Atomic Energy Commission. New York Operations Office, Health and Safety Laboratory, 70 Columbus Ave., New York 23, N.Y. (not dated)

3. Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water. Handbook 52. U.S. Department of Commerce, National Bureau of Standards (1953)

4. Radioactive Waste Disposal in the Ocean. Handbook 58. U.S. Department of Commerce, National Bureau of Standards (1954)

5. The Effects of Atomic Radiation on Oceanography and Fisheries. National Academy of Sciences - National Research Council. Publication 551 (1957)

6. Report of a Meeting of United Kingdom and United States Scientists on Biological Effects of Radiation in Oceanography and Fisheries. National Academy of Sciences - National Research Council. (mimeograph) Oct. 31, 1956.

7. Pathological Effects of Atomic Radiations. National Academy of Sciences - National Research Council. Publication 452 (1956)

8. The Biological Effects of Atomic Radiation. Summary Reports. National Academy of Sciences - National Research Council (1956)

9. Looney, Wm. B. Effects of Radium in Man. Science, 127 No. 3299, p. 630 (1958)

10. Uhlig, H. H.,Corrosion Handbook. John Wiley and Sons, pp. 383-390 (1948)

11. Redfield, A. C. and L. A. Walford, "A Study of the Disposal of Chemical Waste at Sea". Report of the Committee for Investigation of Waste Disposal. National Academy of Sciences - National Research Council. Publication 201 (1951)

12. Reid, R.O. An Analysis of Dispersion of Radioactivity from Local Sources on the Sea Bed. (Unpublished)

13. Taylor, Harden F. A Survey of Marine Fisheries of North Carolina. University of North Carolian Press, Chapel Hill, North Caroline 555 pp. (1951)

CONSIDERATIONS ON THE DISPOSAL OF RADIOACTIVE WASTES FROM NUCLEAR POWERED SHIPS INTO THE MARINE ENVIRONMENT

A report of a working panel of the Committee on the Effects of Atomic Radiation on Oceanography and Fisheries of the National Academy of Sciences—National Research Council, February 1959

PANEL MEMBERSHIP

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PREFACE

In June 1958, the Atomic Energy Commission requested the Committee on Oceanography of the National Academy of Sciences-National Research Council to establish a subcommittee, or working panel, to consider the problem of disposal of radioactive wastes from nuclear powered ships into the marine environment, and to present recommendations which might aid in developing design criteria and operating doctrine relative to waste disposal from such vessels. This request was referred to the National Academy of Sciences Committee on the Effects of Atomic Radiation on Oceanography and Fisheries. In August 1958, the present working panel was appointed.

Following the first meeting of the panel in September 1958, subgroups of the panel collaborated on the preparation of drafts of the various sections of the report. At the second meeting of the full panel, in December 1958, these various sections were reviewed. The present report represents a consolidation of the contributions from the various subgroups into a single document, and was prepared by the chairman of the panel.

SUMMARY AND RECOMMENDATIONS

This report is an evaluation of:

(1) The nature and amount of radioactive waste materials which would conceivably be introduced into the sea through normal operations of nuclear-powered ships. No conclusions are reached concerning the safety of operating nuclear-powered ships in tideless, fresh water bodies.

(2) The routes by which such introduced activity would return to man from the sea.

(3) The portion of the maximum permissible dose to man, allotted to the peaceful uses of nuclear energy, which should be permitted to originate from waste disposal operations from nuclear-powered ships.

(4) The concentration by marine organisms of the various significant isotopes in the wastes.

(5) The processes of dispersion of the wastes within the various subdivisions of the marine environment.

(6) The permissible rate of introduction of the subject waste materials into the various subdivisions of the marine environment.

This report deals specifically with the wastes which would originate from a water-cooled reactor. Other types of reactors will undoubtedly be used in future nuclear-powered ships; the character and amount of wastes which might be introduced to the marine environment from such future designs cannot now be accurately stated. It is believed, however, that the general conclusions of this working panel can be utilized in formulating design criteria and operating doctrine, with respect to waste disposal into the marine environment, for such future types of marine reactors.

In the present report it is assumed that the bulk of the fission products remain contained in the spent fuel elements, and are removed from the ship with these elements at time of refueling. The two principal types of radioactive waste which could enter the marine environment through the normal operation of nuclear-powered ships are: (a) a low-level liquid effluent originating, for the most part, in the primary coolant system; and (b) spent ion exchange resins, used in the bypass cleanup system for the primary coolant. Other possible sources include contaminated expendable tools, glassware, etc., which would be packaged before discharge. The liquid effluent will contain low concentrations of radioactive corrosion products, together with very much lower concentrations of fission products. The ion exchange resins will contain considerably higher activities of these same materials.

The following subdivisions of the marine environment are considered:

(1) Harbors, estuaries, and coastal waters out to two miles from the shoreline;

(2) The coastal area, between 2 miles and 12 miles from the coastline;

(3) The outer continental shelf, extending from 12 miles offshore outward to the 200-fathom depth contour;

(4) The open sea, here considered to comprise those ocean areas more than 12 miles from shore having depths greater than 200 fathoms.

For the last two categories, a further distinction is made between fishing areas and areas which do not contribute materially or directly to the commercial harvest of seafood.

On the basis of reports dealing with the U.S.S. *Nautilus* and the proposed N.S. *Savannah*, a list is made of isotopes with half lives longer than 6 hours which are likely to occur in significant quantities in the primary coolant and the ion exchange resins of marine pressurized water reactors. For each of these isotopes the partial permissible concentrations (ppc) in seafood and the marine environment are determined, for each of the above listed subdivisions of the environment. Assuming that the relative proportions of the various significant isotopes in the wastes do not vary greatly, a weighted mean ppc value for the various subdivisions of the marine environment, for each type of waste, is determined. The relative compositions of the wastes predicted for the *Savannah* and observed for the *Nautilus* differ somewhat, and hence a different weighted mean ppc value is determined for the primary coolant, and for the ion exchange resins, for each of these two types of ship.

The predicted nature and quantity of the potential wastes from the *Savannah*, and the observed nature and quantity of the wastes from the *Nautilus*, are utilized in arriving at the conclusions and recommendations presented here. A similar evaluation can be made for any potential waste of known relative composition, by use of the appropriate weighted mean partial permissible concentration (ppc) values for that waste. If M_i represents the activity in the waste resulting from a given isotope, i, and $(ppc)_i$ represents the partial permissible concentration, for the subject environment, for that isotope, then the weighted mean ppc value for the environment, for that waste, is given by

$$\overline{ppc} = \frac{\Sigma Mi}{\Sigma [Mi/(ppc)_i]}.$$

The weighted mean ppc value is utilized with the gross activity resulting from the isotope mix. It has the advantage of providing a convenient means of including the additive effect of the various isotopes contained in the wastes.

The maximum number of discharges, N, which may be made into a representative segment of each of the subdivisions of the marine environment during any one month period is determined as a function of (a) the total activity in a single such discharge, and (b) the environmental ppc value. These determinations are based on an evaluation of the rates of dispersion and exchange in the marine environment. The limitations to our present knowledge of these phenomena require us to use conservative interpretations of the results. If the permissible number of discharges, for a given activity, into a representative segment of the marine environment is computed to be less than one per month, that environment is considered to be unsuitable as a receiver of that particular waste.

Our conclusions and resulting recommendations for each of the environmental subdivisions are as follows:

(1) *Harbors, estuaries, and coastal waters out to two miles from the shoreline (Zone 1).*—The considerable variation in the physical processes of dispersion within, and exchange between, segments of this marine environment, as well as local variations in the biological and geochemical processes of importance to our problem, makes it impossible to present a completely general conclusion regarding waste disposal into harbors, estuaries, and other inshore areas. Since these are areas of high human activity, it is evident that solid wastes should not be introduced into such wasters. Because of the poor dispersion characterizing tideless harbors which are separated from the sea by locks, it is questionable whether any radioactive wastes should be introduced into such waterways from nuclear-powered ships.

An evaluation is made of a "typical" harbor of poor flushing characteristics. The results are summarized in the following table, which gives the maximum permissible total activity for a single discharge, as a function of selected values of the ppc value for the environment and the maximum permissible number of discharges per month.

ppc value for the environment (μc/ml)	Permissible activity in a single discharge	
	For 1 discharge per month (curies)	For 30 discharges per month (curies)
10^{-9}	2.5×10^{-2}	2.5×10^{-3}.
10^{-8}	2.5×10^{-1}	2.5×10^{-2}.
10^{-7}	2.5	2.5×10^{-1}.

The weighted mean/ppc value for the inshore environment computed for the primary coolant of the *Savannah* is 2×10^{-6} μc/ml, and the predicated gross activity which would be contained in the warmup expansion volume from this primary coolant is 6.8×10^{-1} curies. Hence this "typical" harbor would be unsuitable as a receiver of warmup expansion volume wastes from nuclear powered ships having the activity characteristics predicted for the *Savannah*.

The weighed mean/ppc value for this marine environment computed for the primary coolant of the *Nautilus* is 4×10^{-6} μc/ml, and the observed average activity due to the significant isotopes contained in the normal warmup expansion volume of 500 gal is 1.4×10^{-2} curies. Hence apparently this "typical" harbor could receive a maximum of over 10 discharges per day of warmup expansion volume wastes from nuclear powered ships having the activity characteristics observed for the *Nautilus*.

While relatively poor flushing characteristics were chosen for the harbor used in these sample computations, they do not represent the most restrictive conditions which might be encountered in marine harbors. Also, because of lack of adequate data, it was not possible to include the potential effect on bottom living forms of concentration by the bottom sediments. For these reasons the recommendations which follow are somewhat more conservative than might otherwise be drawn from the above numerical results.

Since the total activities on the spent ion exchange resins, as predicted for the *Savannah* and observed on the *Nautilus*, are 100 to 400 curies, and 12.5 curies, respectively, it is evident that wastes from ion exchange beds cannot be discharged into harbors and other inshore waters.

Our recommendations pertaining to harbors, estuaries, and other inshore environments (Zone 1) are as follows:

Recommendation 1.—No solid radioactive wastes, or spent ion exchange resins, should be discharged into harbors or estuaries, or into coastal waters within 2 miles of the shoreline, from nuclear powered ships.

Recommendation 2.—Nuclear powered surface ships should be equipped with tanks capable of containing any liquid wastes which accumulate during the time such ships are in harbors, estuaries, and other inshore waters, and such wastes should not be discharged until the ship has reached the open waters of the continental shelf. (Restrictions on discharges in this latter environment are treated later in this summary.) Other means of restricting the introduction of such wastes into the inshore environment would also be allowable.

Recommendation 3.—For certain special types of nuclear powered ships, other than surface ships, for which Recommendation 2 would result in significant operational disadvantages, the requirements of that recommendation may be relaxed providing that—

(a) Detailed evaluation of each specific major port of call and harbor base for such vessels be carried out using the general approach outlined in this report, such evaluation serving to establish the permissible activity and frequency of discharge. Actual discharges should be maintained well below the maximum permissible number and activity until the results of detailed environmental monitoring are available, and in any case should be maintained as much below the maximum permissible as is technically feasible.

(b) A detailed monitoring program be maintained, on a continuing basis, in the vicinity of each nuclear ship base and major port of call. (See also Recommendation 11.)

(2) *The coastal area, between 2 miles and 12 miles from the shoreline (Zone 2).*—A 10-mile-wide segment of this subdivision, extending from the inshore edge to the offshore boundary and considered as a ship traffic route, was employed in the sample computations for the coastal area. Because of the possibility of accidental recovery, no solid wastes should be introduced into this environment. The results of the evaluation for the liquid effluent are summarized in the following table, which gives the maximum permissible total activity for a single discharge as a function of selected values of the ppc value for the environment and the maximum permissible number of discharges (N) per month.

ppc value for the environment (μc/ml)	Permissible activity in a single discharge	
	For 1 discharge per month (curies)	For 30 discharges per month (curies)
10^{-6}	5.2×10^{-1}	5.3×10^{-2}.
10^{-6}	5.2	5.3×10^{-1}.
10^{-7}	52	5.3.

The weighted mean ppc value for the coastal area, for the primary coolant of the *Savannah*, is 2×10^{-5} μc/ml and the predicted gross activity which would be contained in the warm-up expansion volume of some 2,200 gal. is 6.8×10^{-1} curies. Thus, considering that it would be unlikely that more than 30 nuclear powered ships per month would pass, outbound, through any such 10 mile wide stretch of the coastal area, this environment appears suitable to receive the low level liquid wastes which would be stored in tanks as a result of restrictions placed on the release of such wastes in harbors.

This zone does not appear suitable, however, to receive the 10 to 400 curie amounts of activity which might be released with the spent ion exchange resins.

Our recommendations pertaining to the coastal area between 2 and 12 miles offshore (zone 2), follow:

Recommendation 4.—Spent ion exchange resins should not be discharged into the waters of the inner continental shelf, between 2 and 12 miles offshore, from nuclear powered ships. The discharge of packaged solid wastes from nuclear powered ships into these waters should conform to recommendations contained in the National Academy of Sciences Report "The Disposal of Radioactive Wastes into the Atlantic and Gulf of Mexico Coastal Waters of the United States" (Carritt, et al., 1959).

Recommendation 5.—Up to five thousand gallons of low level liquid effluent may be discharged as a single release into the waters of the inner continental shelf, between 2 and 12 miles from shore, providing that the total activity contained in any single discharge does not exceed 5×10^{-1} curies resulting from isotopes with half-lives of more than 6 hours.

(3) *The outer continental shelf, from 12 miles offshore to the 200 fathom depth contour.*—The continental shelf off the east coast of the United States was employed in the sample computation for the outer continental shelf. The results of the evaluation for a liquid effluent or for the discharge of ion exchange resins are summarized in the following table, which gives the maximum permissible total activity for a single discharge as a function of selected values of the ppc value for the environment and the maximum permissible number of such discharges per month.

ppc value for the environment (μc/ml)	Permissible activity in a single discharge	
	For 1 discharge per month (curies)	For 30 discharges per month (curies)
10^{-9}	23	2.4.
10^{-8}	2.3×10^{3}	24.
10^{-7}	2.3×10^{4}	2.4×10^{3}.

This region has a much greater capacity for receiving waste materials than the coastal area, and the release of low level liquid wastes from nuclear powered ships into waters of the outer continental shelf apparently presents no serious problem.

For fishing areas of the outer continental shelf (Zone 3a), the weighted mean ppc value for the spent ion exchange resins of the *Savannah* is 2×10^{-8} μc/ml. Since as many as 30 discharges per month onto the continental shelf of the eastern United States could conceivably result from the activity of 300 nuclear powered ships, the maximum permissible activity per discharge would be about 50 curies. Since the predicted activity on the spent ion exchange resins of the *Savannah* will be 100 to 400 curies, it is evident that no release of such resins into fishing areas of the outer continental shelf should be allowed.

For this zone, the weighted mean ppc value for the wastes from the spent ion exchange resins of the *Nautilus* is computed to be 6×10^{-9} μc/ml. The above table then indicates that the gross activity per discharge for such wastes should not exceed about 14 curies, at the rate of 30 discharges per month spread over the entire continental shelf of the eastern United States. This 14 curies is approximately equal to the observed gross activity on the spent ion exchange resins of the *Nautilus*.

For nonfishing areas of the outer continental shelf (Zone 3b), the ppc value for the wastes from the spent ion exchange resins on the *Nautilus* is 3×10^{-8} μc/ml. Thus the gross activity per discharge for such wastes introduced into this environment should not exceed about 70 curies per discharge, for a maximum of 30 such discharges per month randomly distributed over the outer continental shelf off the east coast of the United States. This is approximately equivalent to one discharge per month in any 100 mile wide slice of this shelf.

The continental shelf region selected for the sample calculation may not be the most restrictive segment of the continental shelf of the world ocean, from the standpoint of radioactive waste disposal. Therefore the recommendations which follow are somewhat more conservative than would be drawn from a strict application of the numerical results.

Recommendations for the outer continental shelf, from 12 miles offshore to the 200 fathom depth contour (Zones 3a and 3b), follow:

Recommendation 6.—No discharge of spent ion exchange resins from nuclear powered ships should be made into known fishing areas of the outer continental shelf, from 12 miles offshore to the 200 fathom contour line. Except under very exceptional circumstances there should be no discharge of packaged solid wastes from nuclear powered ships into these waters, and any such exceptional discharge should conform to recommendations contained in the National Academy of Sciences Report "The Disposal of Radioactive Wastes into the Atlantic and Gulf of Mexico Coastal Waters of the United States" (Carritt, *et al.*, 1959).

Recommendation 7.—If denser than sea water, spent ion exchange resins from nuclear powered ships may be discharged into nonfishing areas of the outer continental shelf, from 12 miles offshore to the 200 fathom contour, provided that the activity in any single discharge shall not exceed 50 curies, and also provided that such discharges be restricted to ships which could not, without appreciable loss in efficiency, limit such discharges to waters of the open sea having depths exceeding 200 fathoms. Thus ships inbound from an ocean passage should schedule discharges, which might actually become due during transit of the continental shelf, while still in waters exceeding 200 fathoms in depth. Ships outbound for an ocean passage should delay discharges, where practical, until after having passed into waters of over 200 fathoms in depth. Discharge may be made only when the ship is under way and more than 3 miles from a neighboring vessel.

Recommendation 8.—No restriction need be placed on the discharge of low level liquid effluent from nuclear powered ships into waters of the outer continental shelf, provided that the composition and amount of activity in such wastes are of the same general character as that predicted for the primary coolant of the *Savannah* or observed for the primary coolant of the *Nautilus*.

(3) *The open sea, more than 12 miles from any shore, and having depths greater than 200 fathoms (Zones 4a and 4b).*—This segment of the marine environment has a greater capacity for receiving radioactive wastes than any of the other subdivisions considered in this report. The area of the open sea which is employed in this sample computation consists of the North Atlantic trade route from New York to London. The results of the evaluation for this environment are summarized in the following table, which gives the maximum permissible activity for a single discharge as a function of selected values of the ppc for the environment and the maximum permissible number of such discharges per month.

ppc value for the environment (μc/ml)	Permissible activity in a single discharge	
	For 30 discharges per month (curies)	For 300 discharges per month (curies)
10^{-9}	95	20.
10^{-8}	9.5×10^{3}	2×10^{3}.
10^{-7}	9.5×10^{3}	2×10^{3}.

For fishing areas of the open sea (Zone 4a), the weighted mean ppc value for the spent ion exchange resins of the Nautilus is 1×10^{-8} μc/ml, and for nonfishing areas (Zone 4b), 7×10^{-8} μc/ml. The corresponding values for the *Savannah* are slightly higher. If 300 nuclear powered ships should each discharge spent ion exchange resins 6 times a year, there would be on the average 150 such discharges per month. If all these ships operated along the trade route from New York to London, which has a length of about 6,000 km and a width of about 100 km, interpolation from the above table indicates that the gross activity for a single discharge should not exceed 310 curies for fishing areas of the open sea, and should not exceed 2,200 curies for nonfishing areas of the open sea.

As a result of the recommendations made for the continental shelf, there will likely be some bias in the distribution of such releases in the open sea which would result in a somewhat greater concentration of discharges near the continental slopes. The recommendations for the open sea (Zones 4a and 4b) which are given below reflect this possibility.

Recommendation 9.—Spent ion exchange resins from nuclear powered ships may be discharged into the waters of the open sea at distances of more than 12 miles from shore and in depths greater than 200 fathoms provided that the gross activity of a single such discharge does not exceed 500 curies, that the frequency of such discharges from a single ship does not exceed one per month, and finally, that no such releases be made into the major designated oveanic fishing areas. Discharge may be made only when the ship is underway and is more than three miles from any neighboring vessel.

In view of the distinctions made in these recommendations between fishing areas and nonfishing areas, a further recommendation is required.

Recommendation 10.—The Bureau of Commercial Fisheries of the Fish and Wildlife Service should prepare a chart of the world oceans, showing those areas of the continental shelf and open sea which should be considered as commercial fishing areas. This chart should be issued by the Coast and Geodetic Survey and by the Hydrographic Office, and should be utilized by officers of nuclear powered ships in carrying out the recommendations pertaining to the outer continental shelf and to the open sea given above.

Finally, this working panel makes the following recommendation regarding monitoring and registry:

Recommendation 11.—Immediate steps should be taken to initiate the proposals contained in the section of this report entitled "Monitoring and Record Keeping."

PURPOSE

An unavoidable consequence of the operation of any fission reactor, whether located on land or abroad a nuclear powered ship, is the production of unwanted radioactive wastes. The two general methods of treating these wastes are: (1) containment, coupled with isolation from man's environment; and (2) dispersion, so that the probability of return to man is extremely small. In some case complete containment and isolation are not technically feasible. In other cases such containment and isolation are conceivably feasible, but at high cost.

The purpose of this report is to provide an evaluation of the potential capacity of the marine environment to receive certain radioactive wastes originating from normal operations of nuclear powered ships. Basically, this report is an evaluation of the potential risks involved in utilizing the marine environment in dispersion of these wastes so that the probability of return to any segment of the human population would be small. The conclusions of this working panel can then be employed in weighing these risks against the costs and the risks of alternate methods of waste treatment. Such a comparative evaluation can finally be utilized in the formulation of design criteria and operating doctrine for nuclear powered ships.

SCOPE

This working panel has limited its considerations to the marine environment, No conclusions are reached concerning the safety of operaitng nuclear powered ships in tideless, fresh water bodies. We would assume that before any nuclear powered ship operated on such waterways special consideration would be given to the problems peculiar to that environment by scientists competent in physical, chemical, and biological limnology.

Sepate evaluations are made for: (a) the inshore area, including harbors and estuaries; (b) the coastal area, which is here considered as the area between 2 miles offshore and 12 miles offshore; (c) the outer continental shelf, which is here considered as the area seaward of a line 12 miles from shore and extending to the 200 fathom depth contour; and (d) the open sea, here considered as those oceanic areas more than 12 miles from shore with depths exceeding 200 fathoms.

BRIEF DESCRIPTION OF A NUCLEAR SHIP REACTOR AND ITS OPERATION

In this report, consideraiton has been given primarily to current American practice in the design and operation of water-cooled nuclear reactor systems. There is to date considerable actual operating experience with systems of both the pressurized water and the boiling water type. (Descriptions of these are given in technical manuals covering the Shippingport Atomic Power Station, Shippingport, Pa., the Army Package Power Reactor at Fort Belvoir, Va., the Experimental Boiling Water Reactor at the Argonne National Laboratory, Lemont, Ill., and the Vallecitos Boiling Water Reactor, Vallecitos, Calif.)

Design and operation.—A nuclear reactor for ship propulson replaces conventional boilers fired by fossil fuel. Thermal energy removed by the reactor coolant serves to form steam, either directly or indirectly, to drive the ship's propulsion equipment. Most of the other principal and auxiliary equipment associated with the power cycle is very similar to that used in the conventional marine power system.

In the typical reactor, light water serves as a neutron moderating medium, as well as the heat transfer fluid. The uranium is fabricated in the form of plates or pins, within a cladding, and assembled as conveniently handled fuel elements to form the reactor core. At start-up the excess volume created by thermal expansion of water in some types of systems is displaced as the reactor is brought up to operating temperature. This volume must necessarily be replaced when the reactor is shut down, to assure that the system will be completely filled.

This excess volume from thermal expansion is one of the types of waste with which this report is concerned. As later described, this water contains relatively low concentrations of radioactive corrosion products and may, under some circumstances, also contain a certain variable concentration of fission products. The removal of these materials is generally accomplished by the use of a by-pass purification system through which a portion of the primary coolant is continuously circulated.

Additional sources of liquid radioactive wastes include operational leakage from various components of the primary and auxiliary systems; sampling and laboratory wastes, and those due to equipment decontamination; shower and

laundry wastes associated with the reactor plant. The effluents are collected into holding tanks for storage, decay, and analysis before being either transferred to shore facilities, treated aboard ship, or directly disposed of through controlled discharge overboard.

Shipboard reactors are generally designed to operate continuously for 2 to 3 years on a single loading of fuel ranging up to several thousand kilograms of uranium, depending on the degree of its enrichment. Refueling will be programed insofar as possible to coincide with conventional hull and machinery inspection and maintenance schedules. Liquid wastes associated with refueling will generally include drainage from the primary system, together with effluents from decontamination of reactor components and fuel handling facilities.

As additional experience is obtained in the operation of both land based and shipboard reactor systems, changes will undoubtedly be made in design criteria, selection of materials, and other factors influencing the character and volume of wastes. Other types of reactors will undoubtedly be used in some future nuclear powered ship designs. Thus there are now in progress several feasibility studies of the use of organic moderated and gas cooled nuclear reactors. The character and amount of wastes which might be introduced to the marine environment from such future designs cannot now be accurately stated. It is believed that the general conclusions of this working panel can be utilized in formulating design criteria and operating doctrine, with respect to waste disposal into the marine environment, for such future types of marine reactors. The specific considerations presented here are primarily directed towards the presently planned water-cooled marine reactors.

DEFINITION OF THE TERM "WASTES"

In the normal operation of a nuclear powered ship, as with any conventionally powered ship, liquid effluent will originate from a number of sources. Thus considerable quantities of sea water are circulated through the steam condenser, and discharged back to the marine environment. Sanitary wastes and water used to wash down the decks and for similar normal operating purposes are usually discharged overboard. These liquid effluents would not normally contain any radioactivity resulting from the operation of the nuclear power plant, though it is conceivable that some human or mechanical failure could alter this.

It therefore is desirable, from a practical standpoint, to state some criteria serving to clarify, within the scope of this report, whether a particular effluent could be considered as a radioactive waste or not. For this purpose this working panel suggests the following working definition:

A liquid effluent shall be classed as a radioactive waste if the activity of the undiluted effluent exceeds the mpc values for drinking water for the general public as given in Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised 1959 (proposed).

Solid materials such as trash and garbage are normally discharged overboard from ships at sea. Such material would not be expected to have any activity originating from the operation of the nuclear power plant. In order to cover any eventuality, this working panel suggests that:

Solid materials discharged to the ocean shall be classed as radioactive wastes if the total activity of any whole solid segment exceeds the total activity which would be contained by an equal volume of water having mpc values for drinking water for the occupational worker as given in Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised 1959 (proposed).

POTENTIAL SOURCES OF RADIOACTIVE WASTES

Of all the unwanted radioactive byproducts, or wastes, produced in the operation of a nuclear reactor, the fission products comprise the bulk. Under present and contemplated design, these fission products would be largely contained in the spent fuel elements. Additional wastes result from the induced activity of corrosion products in the primary coolant, together with small amounts of fission products which may be transferred to the primary coolant as a result of minor failures in the cladding of the fuel elements. The amount of radioactive materials in the primary coolant is maintained at relatively low levels by use of a bypass purification system resulting in the accumulation of corrosion product activity, and a considerably smaller amount of fission product activity, on ion exchange resins.

The greater part of the fission products is removed from the ship in the spent fuel elements at the time of refueling. The possible ultimate fate of such high level wastes is beyond the scope of this report. It is, however, a basic assumption of this working panel that these high level wastes do not enter the marine environment through normal operation of a nuclear powered ship. Only in the case of a highly improbable maximum credible accident could any portion of these materials enter the marine environment.

The potential sources of radioactive wastes which might be discharged to the marine environment from nuclear powered ships are, then: (a) the expansion volume of primary coolant during warmup of a pressurized water reactor; (b) operational leakage from various components of the primary and auxiliary systems, and wastes from the laboratory, from sampling, from equipment decontamination, and shower and laundry wastes associated with the reactor plant; (c) ion exchange resins which remove corrosion products from the primary coolant; and (d) contaminated solid materials.

AMOUNT AND COMPOSITION OF WASTES

The amount and composition of radioactive wastes cannot be accurately predicted for all potential marine reactors. In order to have some reasonable basis for evaluation, data for the proposed N.S. *Savannah*, obtained from the Maritime Administration report "Waste disposal considerations in the nuclear powered merchant ship program" (January 1959), have been employed by this working panel as representative of the composition and amount of "typical" potential radioactive wastes from a nuclear-powered merchant ship.

In addition, actual operating data from the nuclear-powered submarine *Nautilus* have been made available in the report "Radioactive Waste Disposal from U.S. Naval Nuclear-Powered Ships" (January 1959) presented for inclusion in the record of the public hearings on industrial radioactive waste disposal held by the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States, January 27 to February 3, 1959. These data have also been utilized by this working panel.

The major source of potential liquid waste is the primary coolant. For the *Savannah*,[1] after 50 days of operation during which a single ion exchange bed has been utilized for bypass cleanup, and assuming 1530 grams of exposed fuel, it is estimated that the concentration of activity of the significant isotopes in the primary coolant will be about 8×10^2 μc/ml. of which the greatest amount will be Cr 51, Co 60, Fe 55, and Ta 182. Sr 90 is estimated to have a concentration in the primary coolant water of 1.4×10^{-7} μc/ml.

The expansion volume during reactor warmup is estimated to amount to about 290 ft^3, or 8.2×10^6 ml. Thus during each warmup a total release of about 6.8×10^{-1} curies would occur. Cr 51 would contribute about 0.4 curie, while Co 60, Fe 55, and Ta 182 would contribute about 0.1 curie each, and Sr 90 would contribute about 1×10^{-6} curies per warmup to the potential liquid effluent. Leakage and other minor sources of liquid waste might contribute 100 gals/day, or 3.8×10^5 ml of liquid effluent of about the same activity as the warmup water. This would be equivalent to a total activity per day of 3.0×10^{-2} curies.

Assuming that each vessel had an average of two warmups per month, the total potential activity in the liquid wastes from one ship during one year's operation would be 16 curies from warmup and 11 curies from leakage and other minor sources.

The ion exchange resins used in the bypass cleanup of the primary coolant would contain far greater activity than that present in the primary coolant itself. It is estimated that in the present merchant ship design these resins, after 50 days of operation, would contain a total activity of about 400 curies, with Cr 51, Ta 182, Co 60, and Fe 55 each contributing about 100 curies. Assuming a change of resin every 50 days, the total activity released per ship per year from this source would be 2,900 curies.

It is estimate in a later section of this report that 300 nuclear-powered ships will be in service by 1975. These 300 ships would then potentially release to the marine environment approximately 2,500 curies per year from expansion

[1] Since completion of this report, subsequent reevaluation of the probable character and activity of the primary coolant and the ion exchange resins has been issued by the Oak Ridge National Laboratory (1959). While this ORNL report includes somewhat different values for the activity in these potential wastes, the general conclusions arrived at here remain unchanged.

water, some 3,400 curies per year from leakage and other minor sources of liquid wastes, and some 9×10^5 curies per year from the ion exchange beds.

According to the report "Radioactive Waste Disposal from U.S. Naval Nuclear Powered Ships," the actual operating results of the U.S.S. *Nautilus* and the U.S.S. *Skate* have produced radioactive wastes considerably less, both in intensity of activity and in amount, than those predicted in the Maritime Administration's report for the *Savannah*. The average gross activity of the primary coolant of the *Nautilus*, 15 minutes after sampling, was 5×10^{-2} μc/ml. However, the bulk of this activity was associated with Mn 56 (2.5 hr half life) and F 18 (1.9 hr half life). The gross activity 120 hours after sampling has averaged 3×10^{-3} μc/ml. The measured activity of Co 60, Fe 59, and Ta 182 has averaged 5.7×10^{-6}, 1.5×10^{-4}, and 7.3×10^{-3} μc/ml, respectively. Fe 55 apparently does not occur in measurable quantities in the primary coolant of the *Nautilus*.

The expansion volume on warmup for the *Nautilus* is much less than that predicted for the *Savannah*, averaging about 500 gals (67 cubic feet). The maximum activity on the spent ion exchange resins in the *Nautilus*, and the rate at which these resin beds require replacement, are likewise much less than the corresponding figures for the *Savannah*. The total activity on the spent resin beds is reported to be no more than 12.5 curies, with the bulk of the activity (some 10 curies) resulting from Co 60. The beds have required replacement about once every six months.

During each warmup involving the average discharge of 67 ft^3 or 1.9×10^6 ml, the *Nautilus* then releases approximately 9.5×10^{-2} curies (measured 15 minutes after sampling). Co 60, Fe 59, and Ta 182 would contribute 1.1×10^{-5} curies, 2.9×10^{-4} curies, and 1.4×10^{-2} curies, respectively. Assuming two warmups per month, the total activity in the expansion volume liquid wastes from the *Nautilus* during one year would be about 2.3 curies measured 15 minutes after sampling and 0.14 curie measured 100 hours after sampling.

In comparison with these amounts, the activity in the fission products contained in the spent fuel elements is quite large. Thus the fission products in the fuel elements from a 60 MW reactor which had been in service for one year on a nuclear powered ship would amount to over 10^7 curies.

It has been stated that the vast majority of the fission product wastes will be stored on land, after chemical separation from unused fuel and useful byproducts. However, even a small fraction of this activity could be significant if released in coastal areas. Release of activity to the coastal environment by land-based nuclear installations, particularly chemical processing plants, may be difficult to avoid. Thus, under a carefully controlled program designed to limit the return of activity to man to a safe level, the Windscale Works in England is authorized to release over 10^5 curies per year into the coastal waters of the Irish Sea. The major part of the safe capacity of these inshore areas should then be reserved for land-based operations, since nuclear powered ships could conceivably delay discharge of wastes until outside such areas.

Nuclear powered ships will spend a part of their time in areas well removed from man, where perhaps the disposal of limited amounts of wastes would not be readily returned to man through the food chain. These ships will also spend part of their time in regions of high human activity, such as harbors and harbor approaches. The release of even very small amounts of radioactive materials in these latter environments might result in the return to man, through the food chain, of undesirable amounts of activity. For this reason even the relatively small amount of activity present in the primary coolant is considered deserving of consideration by this working panel.

PREDICTED NUMBER OF NUCLEAR POWERED SHIPS

In order to properly evaluate the capacity of the various parts of the marine environment to receive radioactive wastes from nuclear powered ships, it is necessary to have a reasonably correct prediction of the number of such ships which will be operating on the world oceans within the next several decades. Efforts of this working panel to obtain such an evaluation have not resulted in consistent estimates, within even an order of magnitude. For this reason the evaluation presented herein is based on an arbitrary number of 300 nuclear powered ships of the 60 MW class. It is believed that this figure should safely apply to the next ten to fifteen years. Adequate time is thus available to revise the conclusions made here on the basis of more dependable estimates of the probable number of nuclear powered ships which will, in the foreseeable future, operate

on the world oceans. Undoubtedly, better information than is now available on the allowable exposure of man to radiation, and on the processes of dispersion, uptake, and concentration in the marine environment, will become available over the next ten years, making such a re-evaluation desirable in any case.

GENERAL APPROACH TO THE PROBLEM

The fate of radioactive material introduced into the marine environment is dependent upon the following considerations:

1. The physical and chemical form in which the material occurs at time of introduction, together with any relatively rapid changes in the physical and chemical character of the introduced material which occur when it is brought into contact with sea water. The subsequent dispersion by physical processes and re-concentration by the biota and bottom materials will be greatly affected by the physical and chemical form in which the wastes occur in sea water.

2. Initial mechanical dilution of the wastes by the receiving waters, which will depend upon the manner of introduction. Thus a liquid waste will be subject to greater initial mechanical dilution if introduced as a strong jet into the body of the receiving waters, than if introduced as a gently flowing stream on the surface. Large initial mechanical dilution is important in reducing the density difference between the initial contaminated volume and the surrounding receiving waters. This reduction in turn favors subsequent turbulent diffusion.

3. Advection of the waste material away from the source region, and simultaneous turbulent diffusion, which lead to reduced concentrations of the radioactive components in the water.

4. Uptake of the activity onto suspended silt and bottom sediments, which removes some of the radioactive materials from the water, and restricts further dispersion. In deep water such removal would be favorable since material incorporated with the bottom sediments there would be unlikely to return to man's environment. In shallow coastal areas containing bottom living shellfish and bottom feeding commercial fin fish, concentration of radioactivity on the bottom may be unfavorable since these detritus and filter feeders may further concentrate the activity from the bottom material.

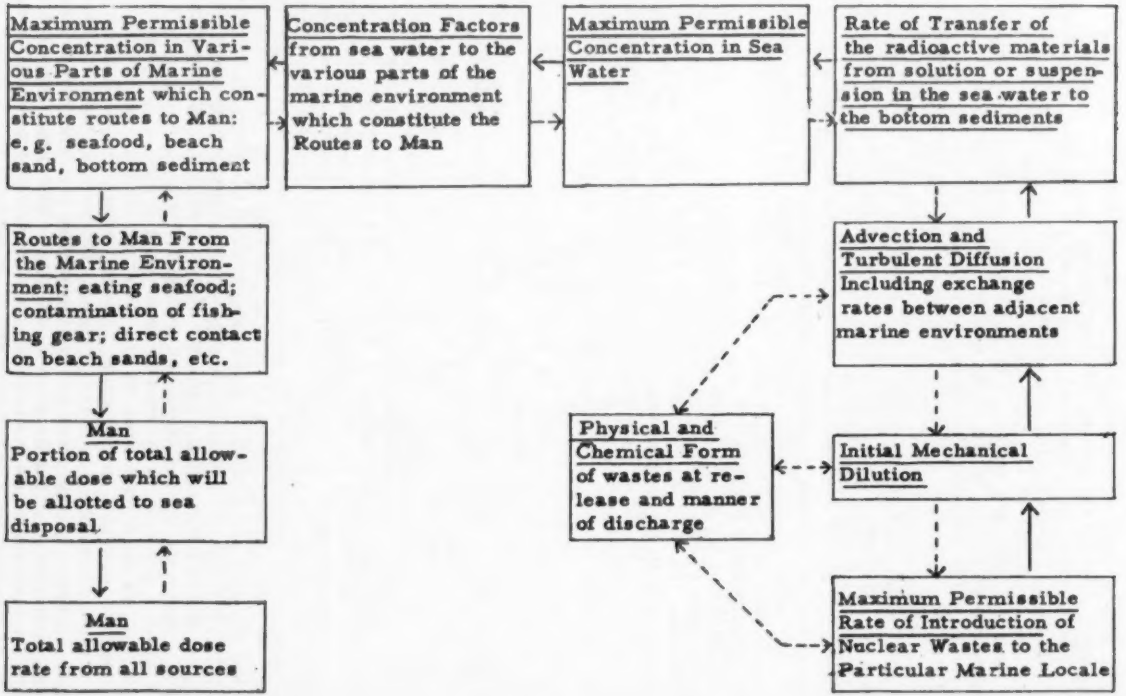
5. Concentration of activity by various parts of the biota, including shellfish and fin fish important to man as a source of food. Some important fission products and corrosion products are concentrated by marine organisms by factors of 100 to 10,000 over the concentrations of these isotopes in the water.

The evaluation of the suitability of any particular marine locality as a receiver of nuclear wastes ideally involves the precise, step-by-step consideration of all factors affecting the possible return of radioactive material to can. The general procedure is the same whether the evaluation concerns: (a) the selection of suitable disposal areas for packaged wastes; (b) the selection of the position of an outfall discharging low level liquid effluent from a chemical processing plant; (c) the consideration of the suitability of a given harbor or harbor approach to receive low level liquid wastes from nuclear powered ships; or (d) the determination of the suitability of the mixed layer of the open ocean to receive wastes from the ion exchange resins on nuclear powered ships. Understanding of many of the physical and biological processes involved is, however, far from adequate, and further research is recommended to provide a more adequate foundation for the determination of the capacity of any particular marine locale to receive nuclear waste materials without undue risks to man.

Figure 1 presents in schematic form such a step by step procedure. The solid arrows between blocks on the diagram indicate the route taken by the radioactive material in returning to man, while the dashed arrows indicate the reverse course taken in the evaluation. The starting point in the evaluation is *man*. In order to make any evaluation of the problem at all, some maximum permissible rate of exposure must be adopted. The usual basis for the selection of such a maximum rate would be the national (or international) published statement of the maximum permissible ingestion rate for the various istopes, for the general population. At the outset it should be recognized that such a maximum permissible rate of exposure is not the most desirable rate. The latter, where technical and economic feasibility allow, should be as close to *zero* as possible. Thus in making this evaluation, some real, though admittedly extremely slight, risk to the general public is assumed.

Figure 1

Schematic Presentation of the Step by Step Considerations which Should be made in Evaluating the Suitability of Any Marine Locale as a Receiver of Nuclear Wastes


Maximum Permissible Concentration in Various Parts of Marine Environment which constitute routes to Man: e.g. seafood, beach sand, bottom sediment
Concentration Factors from sea water to the various parts of the marine environment which constitute the Routes to Man
Maximum Permissible Concentration in Sea Water
Rate of Transfer of the radioactive materials from solution or suspension in the sea water to the bottom sediments
Routes to Man From the Marine Environment: eating seafood; contamination of fishing gear; direct contact on beach sands, etc.
Advection and Turbulent Diffusion Including exchange rates between adjacent marine environments
Man
Portion of total allowable dose which will be allotted to sea disposal
Physical and Chemical Form of wastes at release and manner of discharge
Initial Mechanical Dilution
Man
Total allowable dose rate from all sources
Maximum Permissible Rate of Introduction of Nuclear Wastes to the Particular Marine Locale

Considerable care should be taken in any evaluation that the potential additive effect of exposure to radiation from various sources is given due consideration. The second step in the evaluation is then a consideration of all sources of radiation exposure to the particular segment of the population which would also be potentially affected by the waste disposal operations. On the basis of such consideration a portion of the maximum permissible dose is assigned to sea disposal.

The next step is the consideration of the various routes which the radioactivity can take in reaching man from the marine environment. Here an evaluation of the uses man makes of the marine environment is required. The possible danger of direct radiation, the harvest of seafood, possible contamination of fishing gear and of beach sand are some of the items which should be considered at this stage of the study.

The determination of the maximum permissible concentrations of the various significant isotopes in those parts of the marine environment (seafood, bottom sediments, and shore material) which constitute the routes by which radioactivity may return to man from the sea, then follows as the next step in the process. From a consideration of the known factors by which the biota and the sediment concentrate the various radioactive isotopes from the sea water, it is then possible to arrive at the maximum permissible concentration of the various isotopes in the sea water.

The final steps involve evaluating the changes in the concentration and distribution of radioactivity which may be brought about by—

(*a*) exchange between bottom sediment and suspended or dissolved material in sea water;

(*b*) advection and turbulent diffusion, both within a given marine evironment and between adjacent environments;

(*c*) initial mechanical dilution, influenced by manner of discharge; and

(*d*) physical and chemical form of the wastes at time of release.

The end result is an estimate of the maximum rate of introduction of radioactive material which will not exceed the maximum permissible concentration in sea water.

In the present problem of waste disposal from nuclear powered ships, some modification of this ideal stepwise procedure must be made, since we are not dealing with a fixed region of the marine or coastal environment. For this reason it has been necessary for this working group to take a conservative (safe) assumption at each step of the evaluation. Thus, for inshore and coastal environments, when considering the return route to man of radioisotopes through seafood, the assumption used here is that man receives all his protein requirement from seafood, and that the highest known concentration factor for the particular isotope to the edible marine biota is applicable. Any specific evaluation of a particular marine locale, such as a habor in which nuclear ship testing and servicing are carried out, or which serves as a primary port for nuclear powered vessels, can be based on the study presented here, taking into account the actual utilization of that particular marine environment by man.

BIOLOGICAL SIGNIFICANCE OF THE VARIOUS PARTS OF THE MARINE ENVIRONMENT

With respect to the various physical and biological processes leading to contamination of man's food from the sea, the marine environment may be subdivided in the following manner:

1. The nearshore areas, including the intertidal zone of the open coast and the areas which are partially enclosed by land, i.e., harbors, bays, estuaries, lagoons, and passages separated from the open sea by fringing islands.

2. The continental shelf, and overlying waters. The continental shelf is the submarine rim of a land mass. It extends from the beach seaward and ends at a depth of about 200 meters with a slope descending more or less precipitously into the deep sea. It may be only a few miles wide, as it is along the coast of California, or it may reach out over 100 miles into the ocean, as it does off the North Atlantic coast of North America.

3. The deep sea beyond the continental shelf.

An important further subdivision of the deep sea and the outer continental shelf must be recognized for our purpose. The upper 100 meters (more or less) from the shore outward is a layer in which the water is mixed by various processes brought about by wind and seasonal changes of temperature. A sharp density gradient of considerable thickness separates this mixed layer from the water below, which is generally more stable; the density gradient constitutes a barrier which impedes exchange between the deeper water and the mixed layer.

The nearshore environment is the habitat of commercially important oysters and clams; it is a principal habitat of some highly valued game fishes; it is an essential nursery ground for other commercial species. Seaweed industries gather their raw materials in this area. It is the only part of the sea that can be cultivated like farmland; and it provides exceedingly important fishing grounds for thousands of men, most of them working with small craft.

Upon the continental shelf live many commercially important invertebrates and fish, together with plants and animals of indirect economic value as food for the species utilized by man. Centers of fish population concentration shift diurnally and seasonally. There are few unpopulated areas. Certain commercial species range freely both within and below the mixed layer, over the continental shelf and the deep ocean. We cannot specify any of the marine environments from the land out to the deeper parts of the slopes of the continental shelf which are absolutely devoid of exploited or exploitable food resources, especially as world populations and food needs continue to expand.

GENERAL CONSIDERATIONS ON CRITERIA OF ACCEPTABILITY

The International Commission on Radiological Protection and the U.S. National Committee on Radiation Protection have estimated the maximum permissible total body burden of various radioisotopes and the corresponding maximum permissible concentrations in drinking water. These have been published by the U.S. National Committee in Handbook 52 of the National Bureau of Standards (1953). A revision by the International Commission on Radiological Protection is under preparation; data from this forthcoming revision have been utilized by the AEC in preparing tables contained in Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised 1959 (proposed).

Permissible concentrations in the marine environment are usually calculated on the basis of these maximum permissible body burdens or maximum permissible concentrations in drinking water by: (1) assuming a factor relating maximum permissible exposure of the general population to the maximum permissible exposure as an occupational hazard (Dunster, 1956, for example, used a factor of 1/10; Carritt, *et al.*, 1958, use the mpc's in Handbook 52); (2) calculating, from reasonable and conservative assumptions, the quantity of radionuclides that will reach man from given quantities in the environment. By further considering the relationship between the rate of introduction of a nuclide and the resulting concentration in the environment, there can finally be estimated the maximum permissible rate of discharge into the environment.

This is a reasonable procedure and is similar to the one that this panel has also followed. However, it should not be assumed that the maximum permissible rate of discharge of nuclides into the environment is the sole criterion for determining the acceptable rate of discharge. The *acceptable discharge* should be that quantity, *less than the maximum permissible*, which is reasonable, taking into account the cost of reducing the quantity. In some cases where the cost of alternatives is low and the advantages to be gained by such alternatives are great, the *acceptable discharge of radioactive wastes may be zero.* This is emphasized because, although it has been repeatedly pointed out by other committees dealing with such problems, it has often been ignored.

Both the International Commission on Radiological Protection (1950) and the U.S. National Committee on Radiation Protection (1953) have recommended that exposure to any type of radiation be kept to the lowest level deemed possible or practicable. Evidence that there may be no threshold value for radiation damage, either somatic or genetic, led the U.N. Scientific Committee on the Effects of Atomic Radiation (1958) to the conclusion that any amount of radiation, no matter how small, may be harmful in some degree.

On the other hand, this same U.N. committee (1958) stated that "the possibility cannot be excluded that our present estimates exaggerate the hazards of chronic exposure to low levels of radiation." There is obviously need for much intensive research on all aspects of the problem. For the present, it is evident that the only proper course to pursue, in regard to exposure of man to radiation, is a cautious one.

It should be noted that the maximum permissible concentrations in drinking water tabulated in Handbook 52, and in similar publications, are calculated on the assumption that this is the only source of man's intake of an isotope. If a man is ingesting quantities from several sources, the total intake should not exceed the intake corresponding to the mpc for drinking water times 2,200 (the daily water intake, in milliliters, assumed in Handbook 52). Therefore, in estimating the maximum permissible level in any particular source (such as in food from the sea), account must be taken of all other sources.

On the other hand, care must also be taken to appreciate the full significance of the terms "maximum permissible exposure" and "maximum permissible concentration." These terms, as used here, are based on the effects of continuous exposure to a large human population over the average life span. Thus local, short-term conditions in which concentrations of radionuclides exceed the mpc values may be permissible, provided that the total exposure over a relatively long period of time remains below the required average for that period.

PROCESSES DETERMINING THE CONCENTRATION OF NUCLIDES IN THE MARINE ENVIRONMENT AND IN SEAFOOD

The physical, chemical, and biological processes affecting the distribution of radio-isotopes in the sea have been considered in some detail by Revelle, *et al.* (1957), and the processes in coastal waters particularly have been reviewed by Carritt, *et al.* (1958). It is, however, desirable to consider some of these matters here, with particular reference to the problems of disposal of wastes from nuclear powered ships.

Physical effects.—The oceans are stratified in approximately a two-layer system, with an upper, mixed layer about 100 meters thick, separated from the deeper waters by a region of rapid increase in density, which acts as a barrier to vertical mixing. In partially enclosed basins (harbors and estuaries) interchange between the waters thereof and the waters of the upper mixed layer of the open sea is often inhibited, so that the rate of dilution of pollutant in the water of the basin is a great deal less than the rate of dilution due to eddy diffusion in the open sea. Where the basin has a shallow entrance, there will usually be developed in the basin below the entrance depth a body of water which stagnates seasonally or permanently, and in which there can be a considerable accumulation of elements which fall out as particles from the upper layer. The interchange of water from partially enclosed basins with the open sea depends on a number of factors including (1) the topography of the basin, (2) the amount of fresh water runoff into the basin, (3) the rate of evaporation from the surface, and (4) the tidal and other currents in the waters of the basin. The flushing time (mean residence time of a water particle) is highly variable among estuaries, from a few days to a year or more.

Geochemical effects.—Several things can happen to radioactive materials introduced into the sea as liquid wastes. They may remain in solution or be precipitated out, depending on whether or not the solubility product of the least soluble compound in seawater has been exceeded. Dissolved substances may also be precipitated by coprecipitation with other elements or by sorption on organic or inorganic particles already present in the sea. Both particles and dissolved materials may also be taken up by organisms and enter into biochemical cycles.

Krumholz, Goldberg, and Boroughs (1957) point out that the elements of Groups I, II, V, VI, and VII usually occur as ionic forms in seawater(these include Cs, Sr, Ba, Zr, Cu, Zn, and I) while the other elements, except the rare gases, occur as solid phases (e.g. Y, Fe, Co, and Ru). These authors also tabulate, from Greendale and Ballou (1954), the physical states of elements following detonation of an atomic bomb, which probably also indicates the physical states resulting from waste products introduced into the sea. The material is reproduced here in table 1.

TABLE 1.—*Physical states of elements in seawater (from Greendale and Ballou, 1954)*

Element	Percentage in given physical state		
	Ionic	Colloidal	Particulate
Cesium	70	7	23
Iodine	90	8	2
Strontium	87	3	10
Antimony	73	15	12
Tellurium	45	43	12
Molybdenum	30	10	60
Ruthenium	0	5	95
Cerium	2	4	94
Zirconium	1	3	96
Yttrium	0	4	96
Niobium	0	0	100

Gravity effects on particulate matter in the sea will tend to remove from the seawater radioisotopes incorporated in such particles, which eventually settle to the sea bottom. In the deep sea such sedimentation will remove radioisotopes from the domain of harvested marine organisms. In the near shore and Continental Shelf waters, however, it may tend to concentrate them in the bottom sediments from which they may be returned to the water or taken up by bottom-living food organisms.

Biological effects.—A number of elements are concentrated in the bodies of organisms by several orders of magnitude over their abundance in natural waters. Radioisotopes of such elements are, therefore, concentrated in man's aquatic foods. As pointed out by Ketchum (1957), the concentration of certain elements by organisms, subsequent migration of these organisms, andl gravitational effects on their excreta and remains, all combine to produce a circulation of these elements which differs from the circulation of the water. This is of particular importance in inshore and estuarine waters where, as shown by Ketchum, there may result an accumulation of an element greater than that in the source waters. Revelle and Schaefer (1958) have noted also that "The time required for removal of radioactive materials from estuaries will, in general, be much greater than the flushing time of substances that are not absorbed by organisms or taken up by bottom sediments."

MAXIMUM PERMISSIBLE CONCENTRATIONS IN SEAFOOD

As we have noted above, the maximum permissible body burdens of various radioisotopes and the corresponding maximum permissible concentrations in drinking water as applicable to the general public (calculated under the assumption that this is the *only* source of the ingested isotope) have been tabulated in Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised 1959 (proposed). These are recapitulated in Table 2 for a number of isotopes, including the more important corrosion products and fission products which may occur in wastes from shipborne reactors.

Two additional considerations are required in arriving at the maximum permissible concentrations in seafood which would be permitted to originate from waste disposal operations of nuclear-powered ships. The first of these involves estimation of the amount of seafood which would be ingested, per unit of time, by a segment of the population. The second involves allocating to ship waste disposal a certain share of the maximum permissible dose which man may receive from the utilization of atomic energy. As has been pointed out earlier, food from the sea is not the only source of ingestion of radioisotopes, and nuclear-powered ships are not the only potential source of introduction of radioactive material to the sea. Therefore, it is necessary to decide how much of the maximum permissible intake shall be allocated to the results of waste disposal from nuclear-powered ships.

Since the maximum permissible concentrations so determined apply only to that activity originating from nuclear ship operation, they are actually partial permissible concentrations (ppc's) and are so designated in the remainder of the report.

The evaluation of how much of the maximum permissible intake should be allocated to the results of waste disposal from nuclear-powered ships can be considered in two parts. The first involves an allocation to sea disposal in general. Essentially there are three environments from which man might receive radioactivity; these are the atmosphere, the land (including food and water from the land), and the sea. It is assumed here that sea disposal from all potential sources should be limited to a contribution to a selected portion of the population of no more than one-third of the maximum permissible intake for such a selected portion of the population. This allocation is not intended to specify the manner of subdividing the remaining two-thirds between land and atmosphere.

The evaluation of the remaining factors is somewhat different for each of the major subdivisions of the marine environment. In the following paragraphs the special considerations which apply to the inshore areas, to the continental shelf, and to the open sea are presented.

TABLE 2.—*Data on certain radioisotopes which may be present in waste from nuclear powered ship reactors*

Isotope	Half life	Maximum* Permissible Total Body Burden (μc)	mpc in Drinking** Water (μc/ml)	Partial Permissible Concentration in Marine Food for Cases (see footnotes): (1) (μc/g)	(2) (μc/g)	(3) (μc/g)	(4) (μc/g)	(5) (μc/g)
Cobalt 60	5.2 y	10	3×10^{-3}	3×10^{-3}	6×10^{-3}	3×10^{-4}	1×10^{-4}	7×10^{-4}
Iron 55	2.9 y	1×10^{3}	8×10^{-4}	8×10^{-4}	2×10^{-3}	8×10^{-3}	4×10^{-3}	2×10^{-2}
Iron 59	45 d	20	5×10^{-5}	5×10^{-5}	1×10^{-4}	5×10^{-4}	2×10^{-4}	1×10^{-3}
Chromium 51	27 d	800	2×10^{-2}	2×10^{-2}	4×10^{-2}	2×10^{-2}	1×10^{-2}	5×10^{-2}
Copper 64	12.8 y	10	2×10^{-4}	2×10^{-4}	4×10^{-4}	2×10^{-3}	1×10^{-3}	5×10^{-3}
Tantalum 182	112 d	7	4×10^{-5}	4×10^{-5}	8×10^{-5}	4×10^{-4}	2×10^{-4}	1×10^{-3}
Zinc 65	250 d	60	1×10^{-4}	1×10^{-4}	2×10^{-4}	1×10^{-3}	5×10^{-4}	2×10^{-3}
Cesium 137	33 y	30	2×10^{-5}	2×10^{-5}	4×10^{-5}	2×10^{-4}	1×10^{-4}	5×10^{-4}
Strontium 90	28 y	2	1×10^{-7}	1×10^{-7}	2×10^{-7}	1×10^{-6}	5×10^{-7}	2×10^{-6}
Zirconium 95	65 d	20	6×10^{-5}	6×10^{-5}	1×10^{-4}	6×10^{-4}	3×10^{-4}	1×10^{-3}
Niobium 95	36 d	40	1×10^{-4}	1×10^{-4}	2×10^{-4}	1×10^{-3}	5×10^{-4}	2×10^{-3}
Ruthenium 106	1 y	3	1×10^{-3}	1×10^{-3}	2×10^{-3}	1×10^{-4}	5×10^{-3}	2×10^{-4}
Cerium 144	280 d	5	1×10^{-3}	1×10^{-3}	2×10^{-3}	1×10^{-4}	5×10^{-3}	2×10^{-4}
Iodine 131	8 d	7×10^{-1}	3×10^{-6}	3×10^{-6}	6×10^{-6}	3×10^{-5}	2×10^{-5}	7×10^{-5}

	Concentration invertebrates (edible parts)	Factor*** sea water to— Fish (soft parts)	Fish (skeleton)	Partial permissible concentration in sea water for cases (see footnotes)— (1) μc/ml	(2) μc/ml	(3) μc/ml	(4) μc/ml	(5) μc/ml
Cobalt 60	10^{4}			3×10^{-6}	6×10^{-6}	3×10^{-5}	1×10^{-5}	7×10^{-5}
Iron 55	10^{4}	10^{3}	5×10^{3}	8×10^{-6}	2×10^{-7}	8×10^{-7}	4×10^{-7}	2×10^{-6}
Iron 59	10^{4}	10^{3}	5×10^{3}	5×10^{-6}	1×10^{-6}	5×10^{-6}	2×10^{-6}	1×10^{-7}
Chromium 51	10^{3}(6)			2×10^{-6}	4×10^{-6}	2×10^{-5}	1×10^{-5}	5×10^{-5}
Copper 64	5×10^{3}	10^{3}	10^{3}	4×10^{-6}	8×10^{-6}	4×10^{-7}	2×10^{-7}	1×10^{-6}
Tantalum 182	10^{3}(6)			4×10^{-6}	8×10^{-6}	4×10^{-7}	2×10^{-7}	1×10^{-6}
Zinc 65	5×10^{3}	10^{3}	3×10^{4}	2×10^{-6}	4×10^{-6}	2×10^{-7}	1×10^{-7}	5×10^{-7}
Cesium 137	50	10		4×10^{-7}	8×10^{-7}	4×10^{-6}	2×10^{-6}	1×10^{-5}
Strontium 90	10	1	200	5×10^{-6}	1×10^{-5}	5×10^{-5}	2×10^{-5}	1×10^{-7}
Zirconium 95	2×10^{3}(7)			3×10^{-5}	6×10^{-5}	3×10^{-7}	1×10^{-7}	7×10^{-7}
Niobium 95	200	100		5×10^{-7}	1×10^{-6}	5×10^{-6}	2×10^{-6}	1×10^{-5}
Ruthenium 106	10^{3}(7)			1×10^{-6}	2×10^{-6}	1×10^{-7}	5×10^{-8}	2×10^{-7}
Cerium 144	8×10^{3}(7)	12(8)		1×10^{-9}	2×10^{-9}	1×10^{-8}	5×10^{-9}	2×10^{-8}
Iodine 131	100	10		3×10^{-6}	6×10^{-6}	3×10^{-7}	1×10^{-7}	7×10^{-7}

*From Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised, 1959 (proposed).
**From Title 10, Chapter 1, Part 20, Code of Federal Regulations, Revised, 1959 (proposed), for the general public. Same as 1/10th the falues given in Handbook 52, Revised, 1959 (proposed).
***Data from Revelle *et al.* (1957); Ketchum and Chipman (1958); except as otherwise noted below.
(1) Harbors, estuaries, and inshore waters within 12 miles of the coast line (Zone 1 and Zone 2).
(2) The outer continental shelf, beyond 12 miles from the shore line, in known fishing areas (Zone 3a).
(3) The outer continental shelf, beyond 12 miles from the shore line, in regions not designated as known fishing areas (Zone 3b).
(4) The open sea, in known fishing areas (Zone 4a).
(5) The open sea, in regions not designated as known fishing areas (Zone 4b).
(6) No experimental data. Values approximated on basis of experimental data on biologically similar elements.
(7) Calculated from Martin (1957).
(8) Dunster (1956).

Special considerations related to harbors, estuaries and other inshore waters and to the continental shelf.—An extremely conservative approach is warranted for these waters for the following reasons.

1. Most of the harvest of food from the sea comes from these waters, including the entire harvest of some sedentary forms, such as oysters, scallops, clams, and seaweed, which concentrate certain elements by very large factors. Some large segments of the world population receive the bulk of their protein requirements from this part of the sea.

2. With the continuing development of atomic power, there will inevitably occur a requirement for some introduction of radio-nuclides into the inshore waters from land based establishments; the cost of avoiding this may be prohibitively high. Thus only a portion of the total potential receiving capacity of these waters is available for waste disposal from nuclear powered ships.

3. In the case of a nuclear war, one of the least contaminated sources of food will be the sea. It is, therefore, desirable to keep the radio-isotope contamination prior to this as far below the maximum permissible level as possible.

Some areas of the continental shelf do not contribute materially to the commercial fisheries, and hence some subdivision of this environment might be considered on the basis of known fishing areas. However, it should be remembered that the migratory species travel throughout the waters of the shelf, even though they may not be readily exploitable in some areas. Also some segments of the continental shelf are not now classed as known fishing areas simply because, for one reason or another, they have not yet been exploited. Hence no region of the shelf can be considered as completely devoid of biological significance.

The possible introduction of radioactive wastes into the sea from land based operations will result, for the most part, in contamination of harbors, estuaries, and coastal waters. Hence it may be appropriate to consider waters within an arbitrary twelve miles from the coastline in a different category from the waters of the outer continental shelf. It must be pointed out, however, that this outer continental shelf will very likely be utilized in the disposal of packaged waste material. Hence nuclear powered ships are not the only potential source of radioactive material for these waters.

Considerations relative to the open sea.—Ocean areas more than 12 miles from shore and in which depths exceed 200 fathoms are here considered as open sea. In the open sea there are large areas which do not contribute materially to the commercial fisheries. There are, however, other large areas within which important oceanic fisheries operate, for example the Pacific tuna fishery. The open sea is now being utilized for the disposal of packaged waste material, though these wastes sink to the bottom and the possibility of any significant activity reaching the productive surface layers is slight. Under present doctrine regarding the containment of high level wastes on land, it appears that waste disposal from nuclear powered ships will be the major source of radioactive wastes introduced into the surface layers of the open sea.

Subdivision of the Marine Environments.—On the basis of the above considerations the sea has been divided into six zones, which differ one from another either in terms of potential contribution to the food supply of a selected portion of the population, or in terms of importance as a potential receiver of wastes from sources other than nuclear powered ships, or in terms of the restrictions placed on dispersal within the zone due to physical boundaries. These zones, together with the assumptions required for computation of the partial permissible concentration in seafood in each of the zones resulting from the operation of nuclear powered ships, are listed below:

Zone 1.—Harbors, estuaries, and inshore waters within 2 miles of the coastline. For this zone the assumption is made that a selected portion of the population received all its protein requirement from seafood harvested from these waters. It is further assumed that 30 percent of the maximum permissible dose which this population may receive as a result of sea disposal may be alloted to waste disposal operations from nuclear powered ships in these waters.

Zone 2.—The coastal area, between 2 and 12 miles from the shoreline. For this zone the same assumptions are made as for Zone 1. This zone differs from Zone 1 in that the dispersion is less restricted by physical boundaries.

Zone 3a.—The outer continental shelf, beyond 12 miles from the shoreline, having depths less than 200 fathoms, in known fishing areas. For this zone the assumption is made again that a selected portion of the population receives all its protein requirement from seafood harvested in these waters. It is further assumed that three-fifths of the maximum permissible dose which this population may receive as a result of sea disposal may be allotted to waste disposal operations from nuclear powered ships in these waters.

Zone 3b.—Those areas of the outer continental shelf which are not classified as known fisheries areas. For this zone the assumption is made that these areas contribute, either directly or indirectly through migratory fish, 20 percent of the protein requirement of a selected portion of the population. It is also assumed that three-fifths of the maximum permissible dose which this population may receive as a result of sea disposal may be allotted to waste disposal operations from nuclear powered ships in these waters.

Zone 4a.—The open sea, more than 12 miles from shore and having depths greater than 200 fathoms, in known fishing areas. For this zone the assumption is made that a selected portion of the population receives 50 percent of its protein requirement from seafood harvested in these waters, ad that three-fourths of the maximum permissible dose which this population may receive as a result of sea disposal may be allotted to waste disposal operations from nuclear powered ships in these waters.

Zone 4b.—Those areas of the open sea which are not classified as known fishing areas. For this zone the assumption is made that these areas contribute, either directly or indirectly through migratory fish, 10 percent of the protein requirement of a selected portion of the population, and that three-fourths of the maximum permissible dose which this population may receive as a result of sea disposal may be allotted to waste disposal operations from nuclear powered ships in these waters.

Computation of ppc Values for Seafood.—A human population which obtained all its protein food from marine sources would eat about 1.5 kg per week per person of fish or marine invertebrates. If this food is contaminated with a radio-isotope, and if this is the only source of ingestion of the isotope, we can calculate the maximum permissible concentration in food corresponding to the maximum permissible concentration in drinking water by multiplying the latter by the ratio (water ingested per week)/(food ingested per week) $=\frac{2200\times 7}{1500}=10$.

Designate this factor as N_{wf}. Further, for each of the subdivisions of the marine environment, designate by N_p that fraction of the protein requirement which a significant sized population received from seafood harvested there; designate by N_D that fraction of maximum permissible dose for this population which can be allotted to waste disposal into the sea, and by N_s that fraction of the allotment to the sea which may be utilized for nuclear powered ships within the particular marine subdivision. Then the partial permissible concentration in seafood which can result from the operation of nuclear powered ships, for each of the subdivisions of the marine environment, is obtained by multiplying the maximum permissible concentration for drinking water for the general public by the factor N_m, which is given by $N_m=N_{wf}\times\frac{1}{N_p}\times N_D\times N_s$.

These factors are, for each of the subdivisions of the marine environment:

(1) Zones 1 and 2: harbors, estuaries, inshore waters, and coastal areas within 12 miles of the coastline.

$$N_m=10\times 1\times \tfrac{1}{3}\times \tfrac{3}{10}=1$$

(2) Zone 3a: The outer continental shelf, beyond 12 miles from the shoreline, with depths less than 200 fathoms, in known fishing areas.

$$N_m=10\times 1\times \tfrac{1}{3}\times \tfrac{3}{5}=2$$

(3) Zone 3b: The outer continental shelf, beyond 12 miles from the shoreline, with depths less than 200 fathoms, in regions not designated as known fishing areas.

$$N_m=10\times 5\times \tfrac{1}{3}\times \tfrac{3}{5}=10$$

(4) Zone 4a: The open sea, in known fishing areas.

$$N_m=10\times 2\times \tfrac{1}{3}\times \tfrac{3}{4}=5$$

(5) Zone 4b: The open sea, in regions not designated as known fishing areas.

$$N_m=10\times 10\times \tfrac{1}{3}\times \tfrac{3}{4}=25$$

The partial permissible concentration in marine foods which may be allowed to result from the disposal of radioactive wastes from nuclear powered ships is tabulated in table 2 for each subdivision of the marine environment. As noted in a footnote to Table 2, these calculations have been made on the basis of the mpc's for the general public. These values are lower by a factor of 10 than the occupational values for mpc's given in Handbook 52, and they also include certain revisions which are to appear in the forthcoming new ICRP and NCRP tables.

RESTRICTIONS ON THE APPLICATION OF PPC VALUES IN SEAFOOD AND IN THE MARINE ENVIRONMENT

In applying these ppc values for seafood in the following computation of the ppc's for the various marine environments, and the subsequent use of these latter values in the determination of the safe rate of discharge of nuclides into the various marine environments, the following considerations must be taken into account. The ultimate major source of dilution water for the most restrictive environment (harbors, estuaries, and inshore waters) is the next most restrictive environment, the waters of the continental shelf. Likewise, the ability of the waters of the continenal shelf to receive wastes depends, in part, upon the rate of exchange of these waters with the waters of the open sea. These dilution waters must have, in each case, significantly lower average concentrations than the ppc values of the neighboring more inshore environment. The environmental ppc values computed below thus cannot be considered to represent the average permissible concentration throughout the entire volume of each of the subject marine environments. While these ppc values may apply to substantial areas of each environment in an absolute sense, such areas must be only a relatively small fraction of the entire area of the respective marine subdivision. The manner in which this condition is satisfied is presented in a later section of this report entitled "Basis for Evaluating Safe Discharge Rates."

PARTIAL PERMISSIBLE CONCENTRATIONS IN THE ENVIRONMENT

Having estimated ppc's in marine food organisms, we can estimate ppc's in the environment if we know the factor by which the food organisms concentrate the isotope in question in their bodies from their environment. Concentration factors from sea water to the edible parts of marine invertibrates and marine fishes have been estimated by the authors noted in the footnotes to Table 2. Values are tabulated here for soft (edible) parts of marine invertebrates and for the soft parts and the bones of fish. The latter have been included because some fish (especially canned fish, such as salmon, mackerel, and sardines) are often eaten bones and all. Where the fish bones are eaten, it seems appropriate to use one-tenth of the concentration factor for fish bone (since that is roughly the ratio of bone to whole fish) in obtaining a weighted average concentration factor to use in further computations.

Based on whichever of the concentration factors (that for invertebrates or that for fish) is the higher for each isotope, we have calculated and tabulated the ppc in the environment according to the relation

$$\text{ppc (environment)} = \frac{\text{ppc (food)}}{\text{concentration factor}}$$

The resulting ppc's in the various subdivisions of the marine environment are tabulated in the last five columns of Table 2.

Some investigators have questioned this method of computing ppc values for the marine environment since certain pertinent features of human body chemistry are not evidently included. For the case of strontium 90, an alternate method of computation is based on the so-called sunshine unit. This computation does not explicitly include the concept of concentration factors used in the above evaluation.

On the basis of the allowable body burden in man of strontium 90 and of the total amount of body calcium, it has been shown that, for the population as a whole, the ratio of strontium 90 to total body calcium must not exceed 0.1 μc per kg, i.e.:

$$\text{Sr 90/Ca} \leq 0.1\ \mu\text{c Sr90/kg body Ca.}$$

Man apparently discriminates against strontium in the uptake of calcium and strontium by a factor of 8:1. Therefore, if man receives his total protein requirements from fish, and the fish contains strontium 90, we must have in the fish:

$$\text{Sr 90 / Ca} \leq 0.8\ \mu\text{c Sr 90 / kg Ca.}$$

Assuming that fish do not discriminate against strontium in the uptake of calcium and strontium (probably a conservative assumption), the above limiting relation must also hold for the ratio of strontium 90 to calcium in sea water.

The calcium concentration in sea water of 34% salinity is approximately 400 ppm, or 0.40 g of calcium per kg of sea water. Therefore, there must be less than 0.8 μc of strontium 90 per 2,500 kg of sea water. Hence the maximum permissible value for strontium 90 in the marine environment, assuming that man receives all his protein requirement from fish harvested from that environment, and assuming that this is man's only source of ingestion of radioactive materials would be 3.2×10^{-7} μc/ml. Since for the coastal environment we have assigned only one-tenth the maximum permissible dose to the effects of wastes from nuclear-powered ships, the ppc value for coastal water would be 3.2×10^{-8} μc/ml.

It is seen that this value differs from the corresponding value given in Table 2 by a factor of only about 6.5. The two methods of computation would agree if a concentration factor of about 3, rather than 20, had been used in obtaining the ppc value for the marine environment, for strontium 90, given in Table 2. Thus there is some evidence that slightly conservative values of the concentration factors were employed in computation of the ppc values for the marine environment given in the table.

It is not readily seen how the concept of the "sunshine unit" can be applied to all the radio-isotopes with which we are concerned. Also, in view of the many uncertainties involved, conservative estimates must be made at this time. Hence, for our further computations, the approach used to obtain table 2 is employed by this working panel.

The values thus calculated for PPC's in the environment are probably fairly reliable guides where the "environment" is the water and the food organisms are obtaining their nutrients from the water. This will apply where there is no uptake by organisms of isotopes from bottom sediments.

For food organisms which obtain all or part of their food by ingestion of detritus which has settled on to the bottom (for example the mullet, and some pelecypods and crustacea), we should take account of the concentration factors from bottom sediments to these organisms. Unfortunately, there are no data on this. However, a conservative assumption would seem to be that the concentration factor from bottom sediments to marine food organisms is the same as from water to organisms. Under this assumption, the maximum permissible concentrations in the bottom sediments, for estuarine and inshore waters which support bottom-feeding organisms used as food for man, will be the same as those tabulated for "environment" in Table 2. Since certain of the radio-isotopes with which we have to deal, especially those which occur in particulate form in seawater, may be heavily concentrated in the bottom sediments, this may prove restrictive on the maximum permissible quantities which may be introduced into the superjacent waters.

WASTES FROM NUCLEAR POWERED SHIPS

The Maritime Administration's report (1959) gives data on the expected quantities of various nuclides in the primary cooling water and in the ion-exchangers of N.S. *Savannah*.[1] In Table 3 pertinent data extracted from this report are tabulated for those isotopes in the primary system which present the greatest potential hazard through ingestion in marine food organisms. For the corrosion product nuclides, the report gives the concentration in the system. From this and from the volume of the system (3.9×10^7 ml) the total quantity in the primary coolant has been calculated and tabulated. For the fission products (assuming 1,530 grams of exposed fuel, 100 days operation, and normal purification) the report gives the total quantity of each isotope in the system. These also are tabulated, with the corresponding calculated concentrations in the system.

[1] Since completion of this report, subsequent reevaluation of the probable character and activity of the primary coolant and the ion exchange resins has been issued by the Oak Ridge National Laboratory (1959). While this ONRL report includes somewhat different values for the activity in these potential wastes, the general conclusions arrived at here remain unchanged.

TABLE 3.—*Important isotopes in reactor coolant water, NS "Savannah" (based on estimates made in the Maritime Administration report, 1959)*

Isotope	PPC value for coastal waters μc/ml	Concentration in primary coolant μc/ml	Total amount in primary coolant (curies)	Amount displaced per startup* (curies)
Corrosion products:				
Co 60	3×10^{-9}	1.2×10^{-2}	4.6×10^{-1}	9.8×10^{-2}
Fe 55	8×10^{-8}	1.1×10^{-2}	4.3×10^{-1}	8.9×10^{-2}
Fe 59	5×10^{-9}	5.5×10^{-4}	2.1×10^{-2}	4.5×10^{-3}
Ta 182	4×10^{-8}	1.7×10^{-2}	6.7×10^{-1}	1.4×10^{-1}
Cr 51	2×10^{-6}	4.0×10^{-2}	1.6	3.4×10^{-1}
Fission products: **				
Sr 90	5×10^{-9}	1.4×10^{-7}	$.52\times10^{-5}$	1.2×10^{-6}
Zr 95	3×10^{-5}	1.4×10^{-6}	$.52\times10^{-4}$	1.2×10^{-4}
Ru 106	1×10^{-5}	0.9×10^{-5}	$.34\times10^{-3}$	7.2×10^{-5}
Cs 137	4×10^{-7}	1.5×10^{-4}	$.56\times10^{-2}$	1.2×10^{-3}
Nb 95	5×10^{-7}	1.3×10^{-6}	$.52\times10^{-4}$	1.1×10^{-5}
Ce 144	1×10^{-9}	0.8×10^{-6}	$.31\times10^{-4}$	6.5×10^{-6}
Weighted ppc value and gross activity for above-listed isotopes	2×10^{-5}	8×10^{-2}	3.6	6.8×10^{-1}

*From expansion volume of 290 ft^3=8.2×10^6 ml.
**After 100 days' operation, 1,530 grams fuel exposure, with normal purification.

Since according to the Maritime Administration's report there will be 290 ft^3 of discharge water due to expansion at each startup, it is possible to compute the resulting total amounts of each of the important isotopes which could be displaced per startup. These values are tabulated in Table 3. They may be used together with data from Table 2 to compute minimum necessary dilution volumes. With discharge in an environment (such as the open sea) where the accumulation would be negligible, the minimum necessary dilution volume will be obtained by dividing the partial permissible concentration for the particular subdivision of the marine environment into the amount discharged per startup. For the discharge into a restricted segment of the sea having only slow exchange with the open ocean waters, more complex procedures, discussed later, must be followed.

In Table 4 are recapitulated from the Maritime Administration's report the corrosion products expected to be present in the ion exchange resins of the *Savannah* at time of their discharge. If these are disposed of in the open sea far from known fishing areas, and if the probability of two such discharges occurring in the same vicinity within a period of several days is negligible, the minimum necessary dilution volumes can be calculated by dividing the total activity by the $_{ppc}$ value for the open sea, for regions not designated as known fishing areas. This has been done for the corrosion product isotopes for which data are available.

TABLE 4.—*Important corrosion isotopes in demineralizer after 50 days of operation, NS "Savannah"*

Isotope	PPC value for open sea (non-fishing) μc/ml	Total activity in resin (curies)	Required dilution vol. in m^3*
Fe^{59}	1×10^{-7}	3.8	3.8×10^7
Fe^{55}	2×10^{-6}	75.0	3.8×10^7
Co^{60}	7×10^{-8}	75.0	1.1×10^9
Ta^{182}	1×10^{-6}	103	1.0×10^8
Cr^{51}	5×10^{-5}	148	3.0×10^6
Weighted ppc value (for open sea, nonfishing areas) and gross activity for above listed isotopes	3×10^{-7}	405	1.4×10^9

*For disposal in open sea, in regions not designated as known fishing areas (zone 4b).

The report "Radioactive Waste Disposal from U.S. Naval Nuclear Powered Ships" gives information on the actual observed concentrations of the various radio-isotopes in the primary coolant and on the spent ion exchange resins for

the U.S.S. *Nautilus*. These data are reproduced for the significant isotopes in Tables 5 and 6.

TABLE 5.—*Important isotopes in reactor coolant water, U.S.S. "Nautilus" (average)*

	Ppc value for coastal waters μc/ml	Concentration in primary coolant μc/ml	Amount displaced per warmup* (curies)
Corrosion products:			
Co 60	3×10^{-9}	5.7×10^{-5}	1.1×10^{-5}
Fe 59	5×10^{-9}	1.5×10^{-4}	2.9×10^{-4}
Cr 51	2×10^{-6}	1.0×10^{-3}	1.9×10^{-3}
Ta 182	4×10^{-9}	7.3×10^{-3}	1.4×10^{-2}
Cu 64	4×10^{-6}	1.5×10^{-3}	2.9×10^{-3}
Fission products:			
I 131	3×10^{-8}	1×10^{-5}	1.9×10^{-5}
Sr 90	5×10^{-9}	5×10^{-5}	9.5×10^{-5}
Ce 144	1×10^{-9}	1×10^{-7}	1.9×10^{-7}
Cs 137	4×10^{-7}	1×10^{-6}	1.9×10^{-6}
Weighted ppc value and gross activity for above listed isotopes	4×10^{-8}	7.5×10^{-3}	$1.4^{+}\times10^{-2}$

*From average expansion volume of 500 gals = 1.9×10^{6} ml.

TABLE 6.—*Important corrosion isotopes in spent demineralizer, U.S.S. "Nautilus"*

Isotope	ppc value for open sea (nonfishing) μc/ml	Total activity in resin (curies)	Required dilution vol. in m³ *
Co 60	7×10^{-8}	10	1.4×10^{9}
Co 58		0.5	
Fe 59	1×10^{-7}	0.5	5.0×10^{6}
Cr 51	5×10^{-3}	0.3	6.0×10^{3}
Mn 54		0.2	
Hf 175		1.0	
Weighted ppc value (for open sea, nonfishing areas) and gross activity for above listed isotopes	7×10^{-8}	12.5	1.8×10^{8}

* For disposal in open sea, in regions not designated as known fishing areas (Zone 4b).

The evaluation of permissible rates of discharge of nuclear wastes is complicated by the fact that the potential effluents from nuclear powered ships are composed of a mix of isotopes which may have additive effects on man. In order to include this feature in later computations, it is convenient to determine a weighted mean ppc value for the isotope mix in the primary coolant. This weighted mean ppc value can then be compared with the gross activity resulting from the mix of the significant isotopes listed. In computing the weighted mean ppc value for coastal waters, and the gross activity, which are included in Table 3 for the SAVANNAH primary coolant and in Table 5 for the NAUTILUS primary coolant, only the isotopes listed in these tables have been considered. Very short lived isotopes are not included in the calculation.

BASIS FOR EVALUATING SAFE DISCHARGE RATES

The partial permissible concentrations in the various subdivisions of the marine environment given in Table 2, and utilized by this working panel in the computations which follow, are based on long time exposure of a selected segment of the population. After release of a given volume of liquid wastes or of spent ion exchange resin to the sea water, processes of diffusion will continually reduce the concentration of activity in the water. There will occur a certain period of time during which the activity in a restricted volume of the sea water may possibly exceed the environmental limits which are based on long term exposure. The purpose of the following development is to provide criteria which would insure that no significant volume of a given marine locale would have an average activity exceeding the mpc value for that locale over a significant period of time.

Let A designate the area of a particular marine region within which N discharges of radioactive materials are made during the time period T. Further designate by $t_{1/2}$ the time interval required to replace 50% of the water in the area A with new water from an adjacent, uncontaminated area. The area A must be chosen such that the N contaminated volumes are randomly distributed throughout the area, as a result both of variations in the discharge site and of the movement of the contaminated volumes by currents. The time period T must be short compared to a man's lifetime, but long compared to the time required for the maximum concentration of activity from a point source discharge to be reduced by processes of dispersion to less than ppc values for the environment.

The concentration of activity at a given position and a given time which results from a single discharge is designated by s, and the increment of area within which the concentration varies from $s - \frac{1}{2}$ ds to $s + \frac{1}{2}$ ds during the increment of time dt is designated by dA. Further, let the total area within which the concentration at any time t exceeds the ppc values for the environment be designated by A_{ppc}, and let the time required to reduce the concentrations everywhere in the area to less than ppc values be designated by t_{ppc}. The double integral

$$\int_0^{t_{ppc}} \int_0^{A_{ppc}} sdAdt$$

then represents the total activity, per unit of depth, which occurs in the area having concentrations exceeding ppc values, times the time interval during which the concentration exceeds that critical value. The area of "new" water available each time period T for dilution is given by $AT/_{2t1/2}$.

Hence the relationship

$$\frac{2Nt_{\frac{1}{2}}}{ATT^2} \int_0^{t_{ppc}} \int_0^{A_{ppc}} sdAdt$$

then defines a mean concentration for the total area A during the time period T, resulting from N discharges, each having the same amount of activity. This relationship serves to establish the criteria for evaluating the suitability of any particular marine area as a receiver of radioactive wastes from nuclear powered ships.

If the distribution of contaminated volumes within the area were truly random at all times, and if the processes of biological concentration of radioisotopes were instantly reversible, then a suitable criterion for safe discharge to the marine environment would be the requirement that the mean concentration defined by the above relationship be less than the PPC value (here designated as s_{ppc}) for that environment. Unfortunately, marine organisms which take up radioisotopes when in contact with sea water of a given concentration of activity, do not readily reach a new equilibrium when exposed to water of much lower activity. Also, it would be difficult to assure a completely uniform distribution of the contaminated volumes within the subject area. Finally, and perhaps most important, the condition discussed in the previous section entitled "Restrictions on the Applicaton of ppc Values in Seafood and in the Marine Environment" must be satisfied. Therefore, the criterion employed here is that the mean concentration defined by the above relationship be 1/100th of the ppc value for the environment; that is, the number of releases N in the area A during the time period T must satisfy the relationship

(1) $$N < \frac{ATT^2 s_{ppc}}{200t_{\frac{1}{2}} \int_0^{t_{ppc}} \int_0^{A_{ppc}} sdAdt.}$$

This relationship is utilized in subsequent sections of this report to determine the limits of activity which may be introduced into the various segments of the marine environment without undue risk to man.

EVALUATION OF HARBORS, ESTUARIES, AND OTHER INSHORE ENVIRONMENTS (ZONE 1)

In this section the question of whether harbors, estuaries, and other inshore environments may serve as suitable receivers of any radioactive wastes from nuclear powered ships is investigated. For the present purpose, inshore areas are those coastal regions within two miles of the shore.

Harbors, estuaries, and other inshore environments are regions of high human waterborne activity. This fact, coupled with the normal relatively shallow depths in such environments, argues for a relatively high probability of accidental recovery of any solid wastes introduced there. It is therefore concluded that no solid wastes, packaged or otherwise, should be released in harbors or other nearshore environments. Our attention is then confined to liquid wastes which might be discharged in such waters.

The potential sources of low level liquid wastes which would occur under normal operation of a nuclear powered ship using a water cooled reactor have been described in an earlier section of this report. The fate of such wastes introduced into the marine environment will depend upon the following three processes:

(1) *Initial dilution*, resulting from the mechanical mixture of the effluent with the receiving waters. This initial mixing depends upon the manner in which the effluent is introduced into the receiving waters. Thus a strong jet of effluent introduced below the surface of the receiving waters would result in a mechanical entrainment of the diluting waters until the energy of the jet was dissipated. A gentle flow of effluent at the surface of the receiving waters would result in relatively little initial dilution.

(2) *Advection* of the effluent with the currents in the harbor or harbor approach and simultaneous *turbulent diffusion* leading to further reduction in concentration.

(3) *Concentration* of activity from the water to the suspended silt, the bottom sediments, and the biota.

There is no way that man can directly influence the processes of *advection, turbulent diffusion, and concentration* in a given environment. Man can, however, influence the degree of *initial mechanical dilution* through proper design of the discharge assembly. Since the rate of dispersion through turbulent processes is scale dependent, man can then indirectly influence the natural diffusion of the wastes by increasing the degree of initial mechanical dilution. Also, initial mechanical dilution reduces the density difference between effluent and receiving waters, and hence aids diffusion. Considering the volumes of liquid effluent involved (a maximum of approximately 300 ft^3), the incorporation of a discharge assembly capable of supplying an initial mechanical dilution of 100:1 should be no problem.

Factors such as current velocity, depth, density stratification, wind velocity and fetch, and density difference between effluent and receiving waters all influence the process of turbulent diffusion. Since these factors differ so markedly from one harbor environment to another, it is virtually impossible to make any precise general statement regarding the subsequent fate of liquid wastes discharged into harbor environments. The degree to which harbors, harbor approaches and other inshore environments might be utilized as receivers of liquid radioactive effluent from nuclear-powered ships must ultimately be determined through an evaluation of each specific location involved.

We can, however, consider the general characteristics of certain types of harbors, with the purpose of determining whether there is any possibility of utilization of any considerable fraction of the harbor environments as receivers of liquid effluent from nuclear ships. Thus some important world harbors are approached through locks which limit exchange with the open coastal waters. In most cases such harbors contain fresh water or water of very low salinity. The absence of tidal currents limits the turbulent diffusion within such harbors, and the lack of free exchange with the open coastal waters would result in accumulation within the harbor of any waste disposed therein. It therefore appears unlikely that harbors located in tideless basins, connected to the sea by a system of locks, can be utilized as receivers of any effluent from nuclear-powered ships.

Another group of harbors are located well up estuaries of major river systems, and are characterized by fresh water, though tidal currents of significant magnitude may occur. Possible restriction on the use of such harbors as potential receivers of liquid effluent from nuclear ships is not so much due to the lack of mechanism (such as tidal currents) to induce appreciable turbulent diffusion

within the harbor, but rather due to the much larger concentration factors to the biota which occur in fresh water as compared to sea water.

The majority of harbors throughout the world are, however, located in the lower reaches of tidal estuaries or in costal embayments. The waters of these harbors are normally characterized by salinities of from one-quarter to three-quarters that of full sea water; they are influenced to some degree by tidal currents and wind induced motion; and these harbor waters exchange, to a greater or lesser degree, with the adjacent coastal waters.

Consider such a harbor having a volume V and an exchange coefficient of γ (per day). The exchange coefficient is the fraction of the volume of the water in the harbor which is renewed each day by exchange with the adjacent coastal waters, and by inflow of land drainage. γ is thus comparable to the radioactive decay coefficient, and a "half-life" for the harbor water can be defined in the same way as radioactive half-life. The $t_{\frac{1}{2}}$ in equation 1 is then the half-life of the area, and is related to γ by $t_{\frac{1}{2}}=0.693/\gamma$.

Further, consider a particular discharge of effluent into the harbor. Following the initial mechanical dilution, turbulent diffusion will lead to further dilution at approximately an exponential rate, at least during the early stages of diffusion when contaminated volume is small compared to the volume of the harbor.

A major part of the analysis of the problem of disposal of nuclear wastes into the sea and coastal waters requires sufficient knowledge of the rates of mixing so that the dilution of any introduced liquid can be correctly estimated.

The diffusion model employed in this analysis.—It has always been difficult to make such an estimate because of the lack of a satisfactory general theory of diffusion in the sea; rates of diffusion (the so-called eddy diffusivity coefficients) required by existing theory were adequately known only for certain special cases where direct measurements had been made. Recently, however, Joseph and Sender (1958) have proposed a horizontal diffusion equation which seems to permit a useful statistical description of the time change of concentration of a diffusing substance. The following paragraphs discuss the application of this diffusion equation to the problem of waste disposal from nuclear powered ships.

Joseph and Sender consider the introduction at time t=0 of an amount M of a substance into a small area either of the sea surface or at some deeper level. This small area is regarded as the "point" source for isotropic horizontal diffusion along a thin homogeneous and isentropic layer. After time t the distribution is described by concentric isopleths around the point of maximum concentration. This point is not fixed but moves downstream with the prevailing current. It is further postulated that the velocity of a diffusing particle is independent of distance from the origin, but that the mean dispersion increases in linear fashion with increasing distance.

The following diffusion equation was derived:

$$\frac{\partial s}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[Pr^2\frac{\partial s}{\partial r}\right]$$

where s is the concentration, r the distance from the origin, and P the constant mean velocity of diffusion. Solution of this equation gives:

$$s=\frac{M}{2\pi(Pt)^2}\exp\left[-\frac{r}{Pt}\right] \tag{2}$$

where s and M refer to the concentration and total amount introduced of a given isotope. Note that concentration in this equation has the dimensions ML_{-2}; in applying the equation, volume concentrations can be obtained by using an estimated layer thickness D as the third dimension.

The diffusion velocity P of this equation is related to the Fickian coefficient of eddy diffusivity A by the equation

$$A=\frac{Pr.}{2}$$

Joseph and Sander examined quantitative descriptions of diffusion in a variety of situations in the ocean and found P to be relatively constant with a value of about 1 cm/sec.

This equation applies to a region of unrestricted horizontal dimensions. In restricted waterways, or near shore, the boundaries would limit diffusion. The principle of reflection of the solution obtained by Joseph and Sender, so that the angular range within which diffusion can occur is limited in accordance with the existence of a boundary, can be employed to obtain an approximate equation for use in harbors and other restricted waterways. Thus diffusion of a substance released near an open shoreline would be limited to an arc of 180°. In such a case the reflection of the solution given by equation 2 would produce exactly the same equation, except that the right side would be multiplied by a factor of 2. In an elongated, restricted waterway in which the boundaries restrict diffusion to an arc of, say, 30° in the up-channel and 30° in the down-channel direction the approximate equation for the concentration of a diffusing substance released as a point source would be obtained simply by multiplying the right side of equation 2 by the factor $360°/2 \times 30° = 6$. Thus:

$$s(r,t) = \frac{6M}{2\pi(Pt)^2} exp\left[-\frac{r}{Pt}\right]. \tag{3}$$

If θ_n designates the arc within which diffusion is constrained by the boundaries, then, letting

$$n = \frac{360°}{\theta_n} \tag{4}$$

we have in general

$$s(r,t) = \frac{nM}{2\pi D(Pt)^2} exp\left[-\frac{r}{Pt}\right] \tag{5}$$

where s(r, t) is here concentration per unit volume, since the factor 1/D has been entered into the right side of the equation.

The maximum concentration occurs at the center of the diffusing volume, and is given by

$$s_o(t)2 = \frac{nM}{2\pi D(Pt)^2} \tag{6}$$

At the center the concentration decreases continually with time.

At any distance r from the center, the concentration first rises to a maximum value, and thereafter decreases with time. Thus, assuming that the introduction is truly a point source (i.e., neglecting initial mechanical dilution) there will be, for any finite amount of radioactive wastes introduced, an area within which the concentration exceeds, for a time, the ppc values for the environment. This area will at first increase in size to a maximum value, and thereafter will decrease in size until a time is reached at which the concentration is everywhere less than ppc values. This time can be obtained from equation 6 by setting $s_o(t)$ equal to the ppc value for the particular isotope in question. Thus

$$t_{ppc} = \sqrt{\frac{n}{2\pi DP^2}} \sqrt{\frac{M}{s_{ppc}}} \tag{7}$$

where t_{ppc} is the time after which the concentration everywhere is less than the ppc concentration, which is here designated by s_{ppc}.

Equation 5 can be solved for the distance, at any time t, at which the concentration has just reached ppc values, by setting s(r, t) equal to s_{ppc}. Thus:

$$r_{ppc} = Pt\ln\frac{nM}{2\pi D(Pt)^2 s_{ppc}} \tag{8}$$

The increment of area which, during the time interval t to t+dt, has a concentration varying from s−½ ds to s+½ ds, is given by:

$$\frac{2\pi r dr}{n}$$

and hence the integral which appears in equation 1 is given by

$$\int_o^{t_{ppc}} \int_o^{A_{ppc}} s dA dt = \int_o^{t_{ppc}} \int_o^{r_{ppc}} s \frac{2\pi r dr}{n} dt = \int_o^{t_{ppc}} \int_o^{r_{ppc}} \frac{Mr}{D(Pt)^2} e^{-r/Pt} dr dt.$$

This integral can be evaluated using equations 5, 7, and 8. The solution is given by

$$\int_o^{t_{ppc}} \int_o^{A_{ppc}} s dA dt = \frac{4}{9} \frac{M}{D} t_{ppc}. \tag{9}$$

The criterion for establishing the number of discharges, N, each of strength M, which may be made into a marine locale of area A during the time interval I is then, from equation 1—

$$N \leqslant \frac{9DAT^2 s_{ppc}}{800 t_{1/2} M t_{ppc}} \tag{10}$$

The time period T, which must be short compared to a man's life span, but long compared to the time required to reduce the maximum concentration resulting from a single release to below ppc values, is here taken as 30 days.

Now consider a harbor having relatively poor mixing characteristics and a low rate of exchange with adjacent coastal waters. A review of available data indicates that most marine harbors of the United States have a half life of 30 days or less. Joseph and Sender (1958) found that for a number of phenomena of varying scale in the open sea the diffusion velocity P was nearly constant at 1 cm/sec. A conservative estimate of this parameter for inshore tidal waters is taken at 0.5 cm/sec. Further, assume that in this "typical" harbor the depth interval within which vertical mixing occurs is at least 6 meters. The boundaries of the harbor are considered to constrain diffusion to within an arc of 30°, both up-channel and down-channel; hence, n=6.

We take for the volume and surface area of this "typical" small harbor the values $3\times10^8 m^3$ and $5.4\times10^7 m^2$, respectively. Letting D=6 meters, $t_{1/2}$=30 days and T=30 days, then, for this sample computation in a "typical" harbor of poor flushing characteristics, equations 6, 7, and 10 become

$$s_o(t) = 6.4\times10^3 \frac{M}{t^2} \tag{11}$$

$$t_{ppc} = 0.80\times10^3 \sqrt{\frac{M}{s_{ppc}}} \tag{12}$$

$$N \leqslant \frac{9.5\times10^{12}}{\frac{M}{s_{ppc}} \times t_{ppc}} = \frac{1.2\times10^{11}}{\left(\frac{M}{s_{ppc}}\right)^{3/2}} \tag{13}$$

where s_{ppc} and $s_o(t)$ are expressed in $\mu c/ml$, M in curies, t and t_{ppc} in secs, and N in discharges per month.

An inspection of Tables 3 and 5 reveals tht most of the significant isotopes in the primary coolant have ppc values for coastal water between the values 10^{-7} $\mu c/ml$ and 10^{-9} $\mu c/ml$. Table 7 presents, for this range of ppc values, some sample computations of the time (t_{ppc}) for the maximum concentration resulting from a single discharge of M curies to be reduced to the ppc value for the environment, and the permissible number of such discharges, N, per month, for the "typical" harbor described above. The marine locale is considered unsuitable as a receiver of any discharge for which the value of N is less than 1.0 per month. Thus, for this sample situation, it would be considered unsafe to introduce a single discharge in which the ratio M/s_{ppc} (curies per $\mu c/ml$) was 10^9 or greater. Slightly less than four discharges per month could be made without undue risk for this ratio equal to 10^7 curies per $\mu c/ml$.

TABLE 7.—*Sample computations for a "typical" small harbor of poor flushing characteristics, giving the time (t_{ppc}) for the maximum concentration resulting from a single discharge of M curies to be reduced to the ppc value for the environment (s_{ppc}), and the permissible number of such discharges per month (N) for various values of s_{ppc} in μc/ml*

M/s_{ppc} (curies/μc/ml)	t_{ppc} (secs)	t_{ppc} (days)	N (per month)	M, in curies, for—		
				$s_{ppc}=10^{-6}$	$s_{ppc}=10^{-5}$	$s_{ppc}=10^{-7}$
10^4	8.0×10^3	9.3×10^{-2}	1.2×10^3	10^{-2}	10^{-1}	10^{0}
10^5	2.6×10^4	3.0×10^{-1}	$3.7+10^2$	10^{-1}	10^{0}	10^{1}
10^6	8.0×10^4	9.3×10^{-1}	1.2×10^2	10^{0}	10^{1}	10^{2}
10^7	2.6×10^5	3.0	3.7	10^{1}	10^{2}	1
10^8	8.0×10^5	9.3	1.2×10^{-1}	10^{2}	1	10

These data are presented in graphical form in Figure 2, from which the values of the ratio M/s_{ppc} for N equal to one per month, one per day, and 10 per day have been obtained. Using these ratios, the maximum permissible activities which can be discharged in any single release in this "typical" harbor for the various important isotopes, listed in Tables 3 and 5 for the primary coolant of the *Savannah* and the *Nautilus*, have been calculated for these three rates of discharge. The results are presented in table 8.

This computation applies to the hypothetical case in which the discharge is composed of only a single isotope. For the actual situation the additive effect of the combination of isotopes present must be considered. Assuming that the relative composition of the isotopes in the primary coolant remains fairly constant (a condition which has been shown to exist for the *Nautilus*), then the weighted mean ppc value for the isotope mix may be utilized in computing a permissible gross activity, which can be compared to the gross activity in the actual discharge resulting from the listed isotopes. This has been done for the isotope mix in the primary coolant for both the *Savannah* and the *Nautilus*.

TABLE 8.—*Tabulation, for the discharge of primary coolant expansion volumes into a "typical" harbor of low flushing rate (see text for assumed conditions), of the permissible total activity, for each isotope, per discharge, assuming the discharge contains only that single isotope, and the permissible gross activity for the isotope mix in the primary coolant of the "Savannah" [1] and the "Nautilus" [1]*

Isotope	PPC for coastal waters (μc/ml)	Permissible activity for 1 discharge per month (curies)	Permissible activity for 1 discharge per day (curies)	Permissible activity for 10 discharges per day (curies)
Co 60	3×10^{-6}	7.5×10^{-2}	7.5×10^{-3}	1.6×10^{-3}
Fe 55	8×10^{-4}	2.0	2.0×10^{-1}	4.3×10^{-2}
Fe 59	5×10^{-6}	1.2×10^{-1}	1.2×10^{-2}	2.7×10^{-3}
Cr 51	2×10^{-4}	5.0×10	5.0	.1
Ta 182	4×10^{-6}	1.0	1.0×10^{-1}	2.2×10^{-2}
Cu 64	4×10^{-6}	1.0	1.0×10^{-1}	2.2×10^{-2}
Sr 90	5×10^{-6}	1.2×10^{-1}	1.2×10^{-2}	2.7×10^{-3}
Ce 144	1×10^{-6}	2.5×10^{-2}	2.5×10^{-3}	5.4×10^{-4}
Cs 137	4×10^{-7}	1.0×10	1.0	2.2×10^{-1}
Ru 106	1×10^{-5}	2.5×10^{-1}	2.5×10^{-2}	5.4×10^{-3}
I 131	3×10^{-6}	7.5×10^{-1}	7.5×10^{-2}	1.6×10^{-2}
Primary coolant, *Savannah*	$*2\times10^{-5}$	2.2×10^{-1}	2.2×10^{-2}	4.7×10^{-3}
Primary coolant, *Nautilus*	$*4\times10^{-5}$	8.8×10^{-1}	8.8×10^{-2}	1.9×10^{-2}

[1] Assuming that the isotope mix in the primary coolant is composed of only the isotopes listed in Table 3 for the *Savannah* and Table 5 for the *Nautilus*. Operational experience on the *Nautilus* shows that due to the presence of very short lived isotopes, the measured gross activity of the primary coolant, 15 minutes after sampling, is about 3.5 times the gross activity resulting only from the isotopes listed in Table 5.

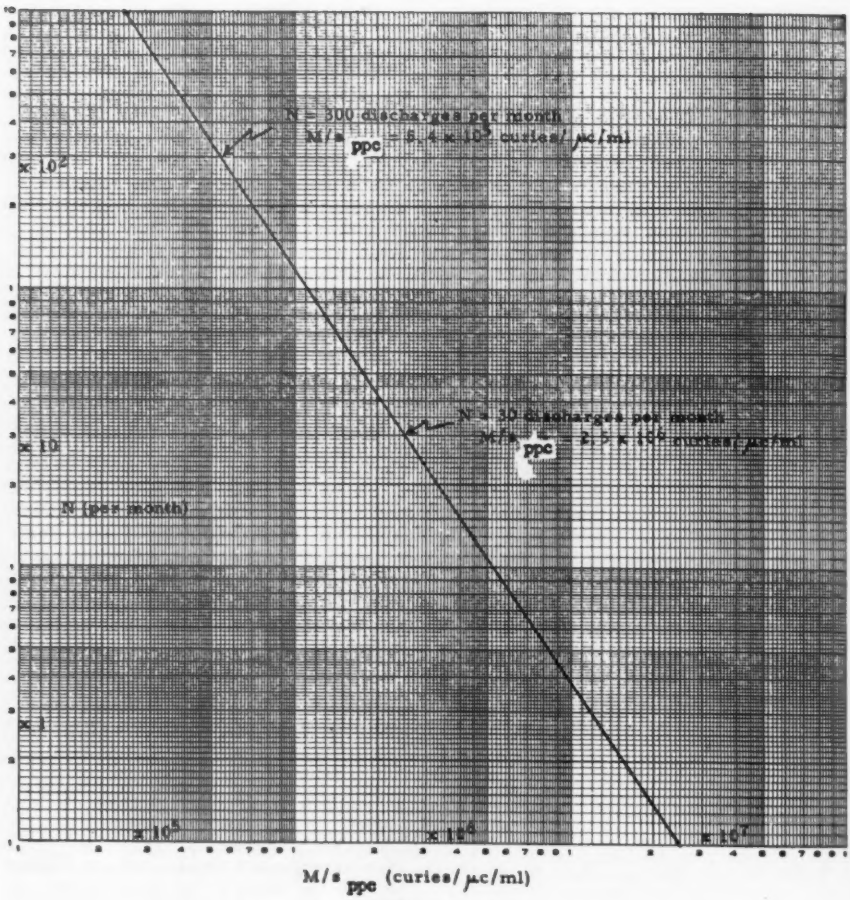


Figure 2

The permissible number (N) of discharges of primary coolant which can be made, per month, into a "typical" harbor, as a function of the ratio of total activity per discharge, M, in curies, to the ppc values for coastal waters in μc/ml.

A comparison of the permissible activities given in Table 8 with the activities which have been predicted to exist in the warmup volume discharge from the *Savannah*, as given in Table 3, indicates that the predicted gross activity due to the listed isotopes exceeds the computed permissible activity even for only a single release per month. Also the predicted activity for Co 60 and Ta 182 both exceed the computed permissible activities for these individual isotopes. It would thus appear undesirable to have a general operating doctrine which would allow liquid effluents of the volume and activity predicted for the warm-up volume of primary coolant from the *Savannah* to be discharged into harbors and estuaries. It should again be pointed out that the basis of this conclusion involves the most conservative (safe) assumptions regarding the eating habits of a selected segment of the population, and also regarding biological uptake of the radio-isotopes. Such assumptions are not unduly conservative for a country such as Japan, where the bulk of the protein requirement is supplied from seafood. The assumptions may well be overly conservative for the coast of the United States. However, recommendations on general operating doctrine for nuclear powered merchant ships must envision these ships operating in areas in which the most restrictive conditions as to waste discharge would apply.

A comparison of the figures in Table 8 with the average measured activities in the primary coolant expansion volumes for the *Nautilus* as given in Table 5 suggests quite a different conclusion. The observed activities for each isotope, as well as the computed gross activity assuming an isotope mix with the observed activities for the listed isotopes, are all lower than the computed maximum permissible activity, even for ten discharges per day. It therefore appears that discharges of liquid effluent in the quantities and activities similar to the warmup volume of primary coolant from the *Nautilus* may be made into the majority of inshore areas without introducing undue risk to man. However, it should be pointed out that the "typical" harbor used in this evaluation, while representing an area of rather poor flushing characteristics, does not represent the worst inshore area from this standpoint.

It is therefore necessary that specific evaluation be made of any harbor or inshore waterway which is to be utilized as a base or as a major port of call for nuclear powered ships. Such an evaluation should include a study of the routes by which activity introduced into the particular harbor or waterway may return to man; of the principal marine products harvested from the area; of the concentration factors to these food products both from the water and from the bottom sediments; and of the physical processes of movement, mixing and exchange of the waters of the particular marine locale.

A similar comparison of the computed permissible activity of a single discharge, with either the predicted activity for the spent ion exchange resins from the *Savannah*, or the observed activity on the resins from the *Nautilus*, contained in Tables 4 and 6, leads to the definite conclusion that spent ion exchange resins should not be discharged in harbors or other restricted coastal waterways.

EVALUATION OF THE COASTAL AREA (ZONE 2)

For this coastal area from 2 to 12 miles offshore, equations 1 through 8 in the previous sections may be utilized, setting $\theta_n = 180°$ and $n = 2$, to take into account the possible limits placed on diffusion by the coastline. A conservative mixed layer depth of 10 meters is taken for this computation. The diffusion velocity P is assumed to be equal to 1.0 cm/sec, which is the value found by Joseph and Sender (1958) for a number of phenomena of varying scale in the open sea.

Releases of wastes from nuclear-powered ships in this regime will probably occur primarily in areas off major ports, with rather definite approach routes. The size of the representative area, A, to be utilized in equation 1 is obtained by considering a 10-mile-wide slice extending seaward from 2 miles offshore to 12 miles offshore. A current parallel to the coastline of velocity less than 1 miles per day would provide for essentially complete replacement of the volume under consideration during the representative time period of 1 month. The value of A is then $3.8 \times 10^8 m^2$, and $t_{1/2}$ equals 15 days.

The pertinent equations, using the symbols introduced in the last section, then are:

$$s_o(t) = 3.2 \times 10^2 \frac{M}{t^2} \tag{14}$$

$$t_{ppc} = 0.18 \times 10^2 \sqrt{\frac{M}{s_{ppc}}} \tag{15}$$

$$N \leq \frac{2.2 \times 10^{14}}{\frac{M}{s_{ppc}} \cdot t_{ppc}} = \frac{1.2 \times 10^{13}}{\left(\frac{M}{s_{ppc}}\right)^{3/2}}. \tag{16}$$

Tables 9 and 10 present the pertinent computations. The probability is extremely small that there will be, on the average, more than 30 of the potential 300 nuclear-powered ships outbound through a single such harbor approach per month. Since the weighted mean ppc for coastal waters, for the isotoype mix in the primary coolant is approximately 10^{-8}, it is evident from a comparison of Table 10 with Tables 3 and 5 that this segment of the continental shelf can safely receive the discharge of warm-up expansion volumes which may have been stored in tanks aboard ship, due to restrictions on the release of this waste into the inshore environment.

TABLE 9.—*Sample computations for a section of the continental shelf 10 miles long extending seaward from 2 miles offshore to 12 miles offshore, giving the time (t_{ppc}) for the maximum concentration resulting from a single release of M curies to be reduced to ppc values for the environment (s_{ppc}), and the permissible number of such discharges per month (N) for various values of s_{ppc} in μc/ml*

M/s_{ppc} (curies/μc/ml)	t_{ppc} (secs)	t_{ppc} (days)	N (per month)	M, in curies, for—		
				$s_{ppc}=10^{-9}$	$s_{ppc}=10^{-8}$	$s_{ppc}=10^{-7}$
10^9	1.8×10^4	2.1×10^{-1}	1.2×10^4	10^{-9}	10^{-1}	1
10^7	5.8×10^4	6.7×10^{-1}	3.7×10^3	10^{-7}	1	10
10^8	1.8×10^5	2.1	12	1	10	10^2
10^9	5.8×10^5	6.7	3.7×10^{-1}	10	10^2	10^3

TABLE 10.—*Permissible total activity per discharge into a section of the continental shelf 10 miles long extending seaward from 2 miles offshore to 12 miles offshore, as a function of the number of such discharges per month and the partial permissible concentration for the coastal waters*

ppc for coastal waters (μc/ml)	Permissible activity for 1 discharge per month (curies)	Permissible activity for 1 discharge per day (curies)	Permissible activity for 10 discharges per day (curies)
10^{-9}	5.2×10^{-9}	5.3×10^{-8}	1.2×10^{-7}
10^{-8}	5.2	5.3×10^{-1}	1.2×10^{-1}
10^{-7}	5.2	5.3	1.2

Since it is considered undesirable to average over a period longer than one month, the maximum permissible amount of activity in a single discharge, even if less than one such discharge were to be made into the subject area per month, is about 5 curies. An inspection of Tables 4 and 6 then indicates that this segment of the continental shelf would be unsuitable as a receiver of spent ion exchange resins.

EVALUATION OF THE OUTER CONTINENTAL SHELF (ZONES 3A AND 3B)

For the region of the shelf from 12 miles seaward to the 200 fathom line, diffusion on a pertinent scale would be unrestricted by horizontal boundaries. Within this area a mixing layer depth of 40 meters may be assumed. Though there are significant areas of this shelf region which are not fished commercially, migratory fish traverse the whole of the continental shelf, and it is not possible to assume that any segment is biologically unimportant, though some parts of the shelf contribute significantly less to the total fisheries than others.

The continental shelf off the east coast of the United States is utilized here as the subject area for our computations of the safe rate of discharge of radioactive wastes from nuclear powered ships into this type of marine environment. The region of this shelf from 12 miles seaward to the 200 fathom line averages about 100 miles in width over the 1,200 mile length of the Atlantic seaboard of the United States. It has been estimated that the average retention time for waters on this shelf is about one year. Hence a conservative estimate of the "new" water area available each month is 1/10th of the total area, or $4 \times 10^{10} m^2$.

For unrestricted horizontal mixing, the value of n in equations 5 through 8 is 1.0. The value of the diffusion velocity is taken as 1.0 cm/sec, as found by Joseph and Sender (1958). The pertinent equations for the required computations then become.

$$s_0(t) = 0.40 \times 10^2 \frac{M}{t^2} \tag{17}$$

$$t_{ppc} = 6.3 \sqrt{\frac{M}{s_{ppc}}} \tag{18}$$

$$N \leqq \frac{2.3 \times 10^{16}}{\frac{M}{s_{ppc}} \cdot t_{ppc}} = \frac{3.6 \times 10^{15}}{\left(\frac{M}{s_{ppc}}\right)^{3/2}} \tag{19}$$

Tables 11 and 12 present the pertinent computations. A comparison of the predicted activities in the primary coolant for the SAVANNAH, given in Table 3, with permissible total activity per discharge, given in Table 11, indicates that no undue risk to man would result from the discharge of several thousand gallons of such effluent as a single release into the waters of the continental shelf seaward of a line 12 miles from the coast. In fact, if each of the potential 300 nuclear powered ships were to make one such release per month into the waters of the continental shelf off the east coast of the United States, the permissible environmental levels would still not be exceeded.

TABLE 11.—*Sample computations for the segment of the continental shelf extending seaward from 12 miles offshore to the 200 fathom depth contour, giving the time (t_{ppc}) for the maximum concentration resulting from a single release of M curies to be reduced to $_{ppc}$ values for the environment (s_{ppc}), and the permissible number of such discharges per month (N) for various values of s_{ppc} in μc/ml*

M/s_{ppc} (curies/μc/ml)	t_{ppc} (secs)	t_{ppc} (days)	N (per month)	M, in curies, for—		
				$s_{ppc}=10^{-6}$	$s_{ppc}=10^{-6}$	$s_{ppc}=10^{-7}$
10^8	6.3×10^4	7.3×10^{-1}	3.6×10	10^{-1}	1	10
10^9	2.0×10^5	2.3	1.1×10^2	1	10	10^2
10^{10}	6.3×10^5	7.3	3.6	10	10^2	10^3
10^{11}	2.0×10^6	23	1.1×10^{-1}	10^2	10	10^4

TABLE 12.—*Permissible total activity per discharge into the segment of the continental shelf extending seaward from 12 miles offshore to the 200 fathom depth contour, as a function of the number of such discharges per month and the partial permissible concentration for the coastal waters*

ppc for coastal waters (μc/ml)	Permissible activity for 1 discharge per month (curies)	Permissible activity for 1 discharge per day (curies)	Permissible activity for 10 discharges per day (curies)
10^{-6}	23	2.4	5.1×10^{-1}
10^{-5}	2.3×10^{2}	24	5.1
10^{-7}	2.3×10^{3}	2.4×10^{2}	51

Table 4 shows that the total activity on the spent ion exchange resins of the *Savannah* is predicted to be about 400 curies after 50 days of operation. Since the ppc value for continental shelf waters, in known fishing areas, for the mix if isotopes shown in Table 4, is about 2×10^{-8} μc/ml, it is evident that not even one such discharge per month into known fishing areas of the continental shelf would be suitable. Even for those areas of the shelf which do not contribute materialy to fisheries, and where a weighted mean ppc value of 1×10^{-7} μc/ml applies, the discharge of 400 curies at one time is not advisable.

On the other hand, Table 6 shows that the total activity on the spent ion exchange resins on the *Nautilus* amounts to about 12.5 curies. The ppc value for fishing areas on the continental shelf for the isotope mix listed in Table 6 is about 6×10^{-9} μc/ml. Setting M equal to 12.5 curies and s_{ppc} equal to 6×10^{-9} μc/ml in equation 19 gives a maximum permissible number of releases per month of 36, or about one per day. In nonfishing areas of the continental shelf, where the environmental ppc value for the isotope mix on the ion exchange resins is about 3×10^{-8} μc/ml, the permissible number of releases of ion exchange resins having the activity reported for the *Nautilus* is computed to be about 20 per day.

According to the report "Radioactive Waste Disposal from U.S. Naval Nuclear Powered Ships," the ion exchange resins in the *Nautilus* require replacement about once each 6 months. Thus, if each of the potential 300 nuclear powered ships were to discharge their spent ion exchange resins twice each year, in a random spatial distribution over the continental shelf of the eastern United States, the environmental limits for this area would not be exceeded, provided that the total activity on the spent ion exchange resins for each ship would not exceed 50 curies.

EVALUATION OF THE OPEN SEA (ZONES 4A AND 4B)

For the purposes of this report, the open sea is considered to consist of those regions of the oceans which are more than 12 miles from any land and which have depths greater than 200 fathoms. The open sea undoubtedly has greater capacity to safely receive radioactive wastes than any of the marine environments previously considered. Since the waters of the outer continental shelf are suitable receivers of the low level liquid effluent from nuclear powered ships, it is evident that no restriction need be placed on the discharge of low level liquid effluent from nuclear powered ships into the open sea. This statement is valid so long as the activities in the liquid effluent are similar to those observed on the *Nautilus* and predicted for the *Savannah*.

The major source of potential wastes for marine disposal on nuclear powered ships are the spent ion exchange resins. According to the report "Radioactive Waste Disposal from U.S. Naval Nuclear Powered Ships", these resins sink in sea water and also rapidly give up the attached active isotopes to the sea water. It is a basic requirement for the application of the findings of this study that in all cases these resins must sink when released into the sea.

In the evaluation of the dispersal of an inoculant in the open sea, using the equations developed by Joseph and Sender, a layer depth of 100 meters is assumed. Since no boundaries exist to restrict horizontal diffusion, at least on the scale of concern here, n in equations 5 through 8 would be equal to unity. The value of P, the diffusion velocity, is taken as 1 cm/sec.

In determining the total area A to be used in evaluating the criteria expressed by equation 1, it is conservatively assumed that all 300 potential nuclear powered ships operate in the New York-London route. The area of this route is estimated at 6×10^5 km^2 (6000 km $\times$ 100 km). The length of the significant time period T is, as in the evaluations for the inshore and continental self areas, taken as 1 month, and $t_{1/2}$ is taken as 15 days.

Equations 6, 7, and 10 then become—

$$s_o(t) = 16\,\frac{M}{t^2} \tag{20}$$

$$t_{ppc} = 4\sqrt{\frac{M}{s_{ppc}}} \tag{21}$$

$$N \leqslant \frac{3.5\times10^{18}}{\dfrac{M}{s_{ppc}}\cdot t_{ppc}} \tag{22}$$

The resulting computations are summarized in Tables 13 and 14. Table 3 shows that the predicted activity on the spent ion exchange resins for the *Savannah*[1] is about 400 curies. The weighted mean ppc value for fishing areas of the open sea, for the isotope mix on the ion exchange resins of *Savannah*, is about 5×10^{-8}. Applying this value to the subject open sea area, equation 22 gives a limiting value of over 10^3 for the permissible number of releases, per month, of 400 curies each. This corresponds to about 30 such discharges per day. In those large areas of the open sea which do not contribute materially to the commercial fishery harvest, the appropriate value for the corresponding environmental ppc is 3×10^{-7}. The permissible number of releases into the subject open sea area would for this case be over 10^4 per month, or 300 per day. Thus, if each of the 300 potential nuclear powered ships should discharge spent ion exchange resins, containing 400 curies each, into the subject open sea area once each 2 months, the permissible limit of radioactivity in the environment would not be exceeded.

TABLE 13.—*Sample computations for a selected trade route area of the open sea, giving the time (t_{ppc}) for the maximum concentration resulting from a single release of M curies to be reduced to ppc values for the environment (s_{ppc}), and the permissible number of such discharges per month (N) for various values of s_{ppc} in μc/ml*

M/s_{ppc} (curies/μc/ml)	t_{ppc} (secs)	t_{ppc} (days)	N (per month)	M, in curies, for—		
				$s_{ppc}=10^{-9}$	$s_{ppc}=10^{-8}$	$s_{ppc}=10^{-7}$
10^9	1.3×10^5	1.5	2.7×10^4	1	10	10^2
10^{10}	4×10^5	4.6	8.8×10^2	10	10^2	10^3
10^{11}	1.3×10^6	15	2.7×10	10^2	10^3	10^4
10^{12}	4×10^6	46	8.8×10^{-1}	10^3	10^4	10^5

[1] Since completion of this report, subsequent reevaluation of the probable character and activity of the primary coolant and the ion exchange resins has been issued by the Oak Ridge National Laboratory (1959). While this ONRL report includes somewhat different values for the activity in these potential wastes, the general conclusions arrived at here remain unchanged.

TABLE 14.—*Permissible total activity per discharge into a selected trade route area of the open sea, as a function of the number of such discharges per month and the partial permissible concentration for the open sea*

ppc for open sea waters (μc/ml)	Permissible activity for 1 discharge per month (curies)	Permissible activity for 1 discharge per day (curies)	Permissible activity for 10 discharges per day (curies)
10^{-5}	9.4×10^{3}	9.5×10	2.0×10
10^{-6}	9.4×10^{3}	9.5×10^{2}	2.0×10^{2}
10^{-7}	9.4×10^{4}	9.5×10^{3}	2.0×10^{3}

CONSERVATIVE AND NONCONSERVATIVE ESTIMATES USED IN THIS REPORT

As a result of the many gaps in our basic knowledge of the pertinent phenomena in the sea which enter into the problem evaluated in this report, it has been necessary for the working panel to include many *estimated* parameters in the evaluation. Because we are treating a problem which is potentially very dangerous to man and to man's utilization of the natural environment, we have in general made conservative (safe) estimates of the uncertain factors. An additional reason for making conservative approximations is that the nuclear ship is not fixed and may travel into marine waters which are most restrictive from the standpoint of dispersion, exchange and biological uptake, as well as being heavily utilized by man.

The following summarizes the conservative approximations made in this evaluation.

1. It is assumed, for coastal areas and fishing areas of the continental shelf, that a selected segment of the population receives all its protein requirement from seafood harvested from the marine area subject to waste disposal. This assumption is not overly cautious for a country such as Japan, but is quite conservative for the United States. This restrictive assumption is relaxed when considering those areas of the outer continental shelf and open sea which contribute little to the fisheries harvest.

2. In computing the distribution of activity with time resulting from a given discharge, the radioactive decay was not included.

3. In computing the effect of discharge of spent ion exchange resins, it was assumed that all the activity was immediately released by the resin to the sea water. This is a conservative assumption only if the resins sink.

4. The effect of initial mechanical dilution on the distribution of activity after release to the marine environment was not included in the computations. This factor would be significant only during the very early stages of dispersion, since the point source solution and the finite source solution to the diffusion equations converge with increasing time. The major importance of initial mechanical dilution would be the reduction of any density difference between the effluent and the receiving waters. The assumption is made that no such density difference exists; hence the major effect of initial mechanical dilution is in fact indirectly included in the evaluation.

5. In the computations for the outer continental shelf and for the open sea, the possible transport of activity out of the surface layer by settling of particulate material was not included. In inshore waters it is possible that this process would be detrimental, since activity could be concentrated onto bottoms where important shellfish and bottom feeding fin fish occur.

6. The highest measured concentration factors for the uptake of a specific isotope by the biota were employed in the calculations, except that where concentration in the skeleton was important, one-tenth of the concentration factor from sea water to bone was used, since bone makes up about one-tenth of the edible portion.

Possible nonconservative features of our estimates include the following:

1. The equations of Joseph and Sender (1958), which were employed in computing the dispersion of radioactive wastes due to turbulent diffusion, are based on a statistical concept which provides a smoothed space and time distribution. A time record of the concentration at any given point, or the spatial record of the concentration at any given time resulting from a single actual point source, would differ in a random manner from the smoothed distribution

predicted by the equations of Joseph and Sender. There would thus occur, from any single discharge, periods of time during which the concentration over small areas would be higher than that predicted. Since there would also occur corresponding times and locations with concentrations less than predicted, and since our concern is, at least in part, with the integrated effect of a number of such releases over time and space, this departure of the actual distribution from the predicted distribution does not introduce serious error in the final computations.

2. In the evaluation of the open sea environment, a 100 meter thick stirred layer was assumed. In some ocean areas this may be too large. In the case of a 10 meter stirred layer, the estimates of the time, t_{ppc}, required for the concentration to be reduced to environmental ppc levels would be increased by a factor equal to $\sqrt{10}$, or approximately 3.2; the corresponding value of N, the allowable number of discharges per month, would be decreased by $\sqrt{10^3}$, or approximately by a factor of 32. Such a small value of the layer depth for the open sea would be very unusual; any real overestimation of this factor is most probably compensated for by the neglect of transport of any activity to the deeper water.

3. In the computations for coastal waters, the possible concentration of activity on the bottom, due to uptake by suspended silts and subsequent settling, was not included. While this would be a conservative factor for those organisms which spend most of their time swimming or drifting in the water, it may well be quite detrimental to bottom living forms, particularly detritus and filter feeders. Data are not available to adequately evaluate the significance of this phenomenon. It is primarily for this reason that our final recommendations relative to inshore waters are more conservative than might otherwise be warranted from a strict application of our numerical results.

MONITORING [2] AND RECORDKEEPING

It is essential that a systematic monitoring program be initiated as soon as possible to determine the consequences of the release of radioactive wastes from nuclear powered vessels, both civilian and military. This program is required in order to protect public health and property, to modify regulations in the light of new knowledge, and to prepare for intelligent action if and when nuclear disasters occur in inshore environments.

This program should be carried out by a single agency of the Federal Government apart from that having regulatory authority. Since the work requires development of techniques for detecting low level radioactivity and for sampling a wide variety of habitats and organisms, and since the nature of the problem will be continually changing with changing technologies of atomic power, the program must have a core of excellent scientists capable of backing a dynamic directorate. In order to attract such people (which is in itself a difficult problem), provision should be made to allow them wide latitude for independent research related to the subject.

The monitoring should cover all harbors in the United States and its territories entered by nuclear vessels, to the extent required by such use. It should be flexible enough to encompass, when circumstances require, all marine environments where organisms are exploited by man. It should be directed towards the detection of the radioactive isotopes produced in both corrosion and fission processes, distinguishing the quantities originating from fallout, from land-based reactors and from nuclear vessels.

Although those engaged in the program must be given wide latitude in its execution, the panel suggests that the following are sensible subjects for observation: commercially useful organisms; certain other organisms that have high concentration factors for any of the radioactive elements; the water and its suspended solids; and the sediments.

In this regard it is recognized that the permissible concentrations recommended for the coastal waters are quite small from the standpoint of detection, and would require special counting techniques to determine. It is, however, not the concentration in the water phase of the environment, but rather the activity in the marine organisms, which is the controlling factor. The

[2] A monitoring program has also been recommended by the Committee on Oceanography of the National Academy of Sciences.

determination of environmental PPC values has been primarily an intermediate step to provide the necessary means of getting from the PPC value for the edible portions of marine organisms to the permissible rate of introduction of radionuclides to the environment. An inspection of Table 2 shows that the PPC values in the marine organisms are generally several orders of magnitude above the corresponding PPC value for coastal water. It is thus obvious that the most profitable method of monitoring the effects of the introduction of nuclear wastes into the marine environment is through measurements on the biota.

All nuclear-powered vessels should be required to maintain a record of all discharges of liquid waste effluent, of ion exchange resins, or of any other materials which, by the definitions used in this report, are classed as radioactive wastes. Such records should give information as to the location and time of each discharge; the concentration, total volume and total activity of each discharge (within the accuracies of available practical techniques for estimating these quantities); as well as an estimate of the isotopic composition of the discharge, with estimates of the amount of activity associated with each of the major constituents. Copies of such records should be transmitted at regular intervals to the appropriate national agency, which will, in turn, supply condensations of these records to any international organization which may, by mutual agreement between governments, assume responsibility on an international basis for the monitoring and registry of nuclear-waste disposal into the ocean.

Provision should be included for the prompt reporting and dissemination of information relative to the emergency or accidental release of radioactive materials in amounts exceeding those recommended in this report.

REFERENCES

Alco Products, Inc. (1955): Description of the Army package power reactor. AECD 3731, October, 1955.

Argonne National Laboratory, University of Chicago (1957): The experimental boiling water reactor. ANL 5607, May 1957.

Carritt, Dayton E., et al (1958): The feasibility of the disposal of low level radioactive wastes into inshore waters of the Atlantic and Gulf coasts of the United States. Mimeographed report to the National Academy of Sciences—National Research Council Committee on Oceanography, prepared by a subcommittee of the Committee on Effects of Atomic Radiation on Oceanography and Fisheries, 36 pp., plus 10 appendices separately paged.

———(1959: The disposal of radioactive wastes into the Atlantic and Gulf of Mexico coastal waters of the United States. Report of subcommittee to Committee on Effects of Atomic Radiation on Oceanography and Fisheries, National Academy of Sciences—National Research Council, 60 pp.

Congress of the United States (1959): Code of Federal Regulations, Title 10, Chapter 1, Part 20, revised 1959 (proposed).

Craig, Harmon (1957): Disposal of radioactive wastes in the ocean: the fission product spectrum in the sea as a function of time and mixing characteristics, *in* Revelle, et al. (1957), pp. 34–42.

Department of the Navy (1959): Radioactive waste disposal from U. S. naval nuclear powered ships. Nuclear Propulsion Division, Bureau of Ships; Iltis, T. J., and Miles, M. E. Mimeographed, presented for the record at the public hearings on industrial radioactive waste disposal, held by the Special Subcommittee on Radiation, of the Joint Committee on Atomic Energy, Congress of the United States, January 27, to February 3, 1959.

Dunster, H. J. (1956): The discharge of radioactive wastes into the Irish Sea, Pt. 2, the preliminary estimate of the safe daily discharge of radioactive effluent. Proc. Int. Conf. on Peaceful Uses of Atomic Energy, Geneva, 1955, Vol. 9, pp. 712–715.

General Electric Corporation (1957): Description of the General Electric developmental boiling water reactor. SG–SVAL–1, Vallecitos Atomic Laboratory; Kornblith, L., Jr., Welsh, L., and Strain, E.

Greendale, A. E., and Ballou, N. E. (1954): Physical state of fission product elements following their vaporization in distilled water and seawater. USNRDL Doc. 436, pp. 1–28.

International Commission on Radiological Protection (1950): Recommendations of the International Commission on Radiological Protection and of the

International Commission on Radiological Units. U.S. Dept. of Commerce, Nat. Bur. Standards Handbook 47.

Joseph J., and Sender, H. (1958): Horizontal diffusion in the sea. Deut. Hydrog. Zeit. *11* (2), pp. 49–77.

Ketchum, Bostwick H. (1957): The effects of the ecological system on the transport of elements in the sea, *in* Revelle, et al. (1957), pp. 52–59.

——— and Chipman, Walter A. (1958): Permissible sea water concentration, monitoring of disposal areas. Appendix VI of Carritt, et al. (1958), 9 pp.

Krumholz, Louis A., Goldberg, Edward D., and Boroughs, Howard A. (1957): Ecological factors involved in the uptake, accumulation, and loss of radionuclides by aquatic organisms, *in* Revelle, et al. (1957), pp. 69–79.

Maritime Administration (1959): Waste disposal considerations in the nuclear-powered merchant ship program. Mimeographed, presented for the record at the public hearings on industrial radioactive waste disposal, held by the Special Subcommittee on Radiation, of the Joint Committee on Atomic Energy, Congress of the United States, January 27, to February 3, 1959.

Martin, DeCourcey, Jr. (1957): The uptake of radioactive wastes by benthic organisms. 9th Pacific Science Congress, November 1957.

National Committee on Radiation Protection, Subcommittee on Permissible Internal Doses (1953): Maximum permissible amounts of radioisotopes in the human body and maximum permissible concentrations in air and water. U.S. Dept. of Commerce, Nat. Bur. Standards Handbook 52, 45 pp.

——— Revised 1959 (proposed).

Oak Ridge National Laboratory (1959): Maritime reactor project, annual progress report for period ending November 30, 1958. ORNL–2657. TID–4500 (14th ed.).

Report of the United Nations Scientific Committee on the Effects of Atomic Radiation (1958): U.N. Gen. Assembly, Official Records, 13th session, suppl. 17 (A13838), 228 pp.

Revelle, Roger, and Shaefer, Milner, B. (1957): General considerations concerning the ocean as a receptacle for artificially radioactive materials, *in* Revelle, et al. (1957), pp. 1–25.

Revelle, Roger, et al. (1957): The effects of atomic radiation on oceanography and fisheries, report of the Committee on Effects of Atomic Radiation on Oceanography and Fisheries, of the National Academy of Sciences Study of the Biological Effects of Atomic Radiation. Nat. Acad. Sci.-Nat. Res. Council Pub. 551, 137 pp.

Technical Information Service, U.S. Atomic Energy Commission (1958): The pressurized water reactor forum, December 2, 1955, held at Mellon Institute, Pittsburgh. TID 8010, February 1956.

Representative HOLIFIELD. We will now hear Mr. Donald Pack of the U.S. Weather Bureau, who will give testimony on meteorological studies.

STATEMENT OF DONALD H. PACK,[10] METEOROLOGIST, DEPARTMENT OF COMMERCE, WEATHER BUREAU

Mr. PACK. Mr. Chairman, members of the commitee, first I would like to thank the committee for the opportunity to make this presentation. Secondly, I hope you will forgive my voice because, in spite of my profession, the weather in the last few days has given me an awful cold.

[10] Born: Oct. 25, 1919, Albany, Mo. Education: St. Joseph Junior College, St. Joseph, Mo.: New York University, University of Chicago (at Puerto Rico). Department of Commerce Weather Bureau—Weather observer, 1940–42: U.S. Air Force, private to captain, 1942–46; Department of Commerce, Weather Bureau, 1946 to present—Meteorologist (California, Alaska, Ohio, Washington, D.C.), associated with nuclear energy field since 1953. Publications include papers at 1st and 2d Conferences on the Peaceful Uses of Atomic Energy. Member: American Meteorological Society, American Geophysical Union, Royal Meteorological Society.

The atmosphere is the most mobile of all geophysical mediums. It can carry material for great distances in relatively short times, crossing geophysical and political boundaries without pause or interruption.

The atmosphere is also an effective dispersing agent and can dilute gases and small particles through a tremendous volume in a relatively short time. In addition, the action of precipitation, and turbulence near the ground, tend to constantly cleanse the air and remove foreign material.

Because of these characteristics of the air its effective use in the disposal of some forms of radioactivity aids in the efficient and economic application of nuclear energy.

However, it has also been the goal to develop the field of nuclear energy so that its effect on the environment is safely negligible. To do this we must understand the environment; in this case we must understand the meteorological variations that control the transport and dilution of material in the air.

There are large variations in the capacity of the atmosphere to disperse radioactivity or any other pollutant. The effects of lakes and mountains, daylight and darkness, winter and summer on the flow of air and its diffusive capacity must be quantitatively measured and then interpreted in terms applicable to the operation of specific nuclear plants.

The problem facing the meteorologist is to measure and interpret weather observations in terms of three areas of application.

First, is site selection and analysis. When a location for a nuclear plant is being chosen it is desirable to compare, along with other physical and economic criteria, the atmospheric transport and dilution potential of several possible sites.

The wind direction frequencies are determined, and related to population distribution; the frequency and persistence of "rapid" and "slow" diffusion periods are examined; precipitation amounts, frequency and concurrent winds are studied; the possibility of local wind channeling or other anomalies is determined.

These and other factors are combined into a site climatology which, when related to the planned nuclear devices, permit intercomparison of various sites. If, however, only a single location is under consideration, a similar meteorological analysis provides valuable design criteria. That is, from the meteorological analysis, it is possible to determine how much more, or less, engineering effort must go into the design of containment vessels, gaseous waste disposal equipment, etc.

Many analyses of this type have been made by the Weather Bureau and by other meteorologists. Figure 1 shows the location of a number of these studies prepared by the Weather Bureau.

This illustration also indicates some of the tools used for field studies—meteorological towers, remote recording wind stations, and atmospheric tracers.

Second, the meteorologist may be required to determine when atmospheric conditions are favorable for the operation of various nuclear devices and even, particularly in the last few years, to forecast the occurrence and duration of such conditions.

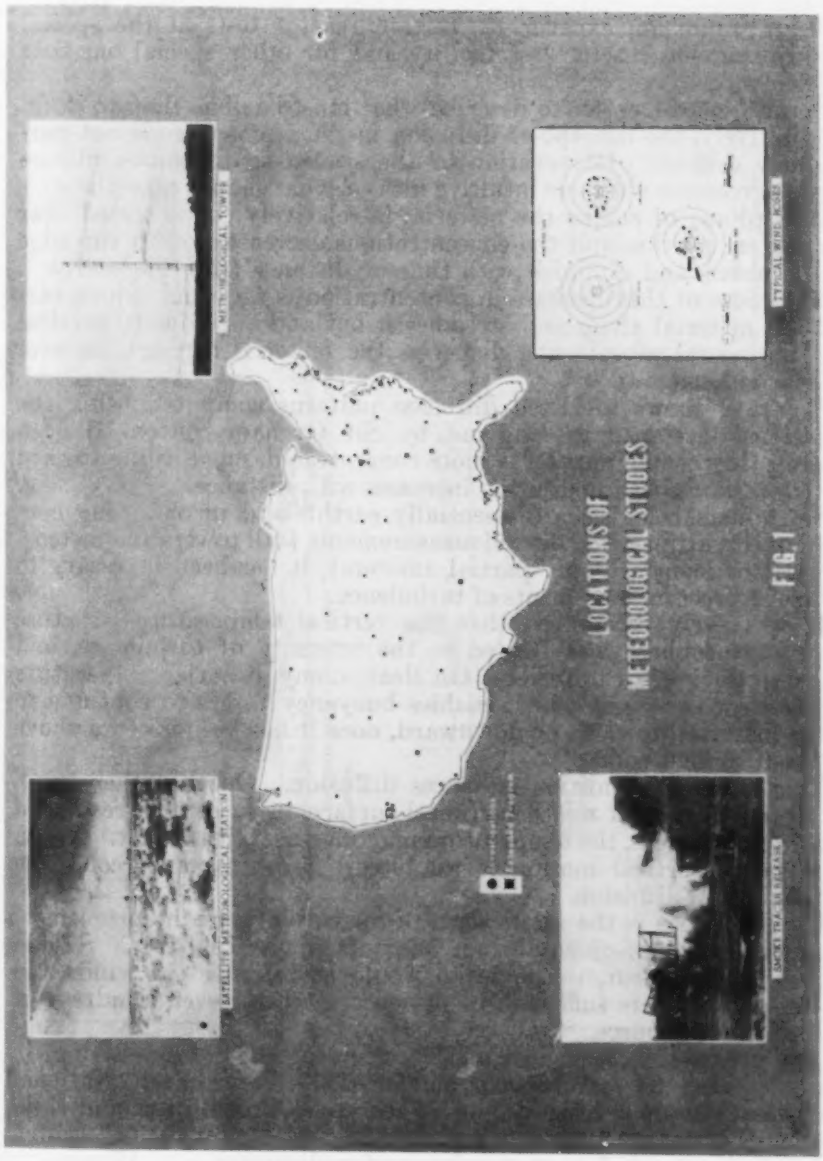


FIGURE 1.—Locations of meteorological studies.

Pioneering work in this field was carried out at Brookhaven National Laboratory where the air cooled graphite reactor operated under "meteorological control"—that is, operations were tailored to fit the weather, for several years.

More recently, the Weather Bureau Office at the National Reactor Testing Station has provided meteorological advice and forecasts for various operations including the chemical processing plant, aircraft nuclear propulsion experiment, certain reactor tests at the special power excursion reactor test facility and for other special one-time experiments.

It is, of course, easier to describe what must be done than to do it. Qualitatively, the concept of diffusion in the atmosphere is not particularly difficult. Observation of the spreading of smoke plumes shows agreement with our intuitive idea of what should take place.

In a plume of smoke the material is relatively concentrated near the central portion and the concentrations decrease toward the edge of the plume and diminish with time or distance from the source.

The cause of this decrease in concentration is the wind, which carries the material along and stretches it out and also, due to vertical and horizontal movements, disperses the material through an ever greater volume.

Figure 2 shows idealized diffusion patterns computed using the equations developed in England by Sir Graham Sutton. It can be seen that center portion is more concentrated, more dilute toward the edges, and that the dilution increases with distance.

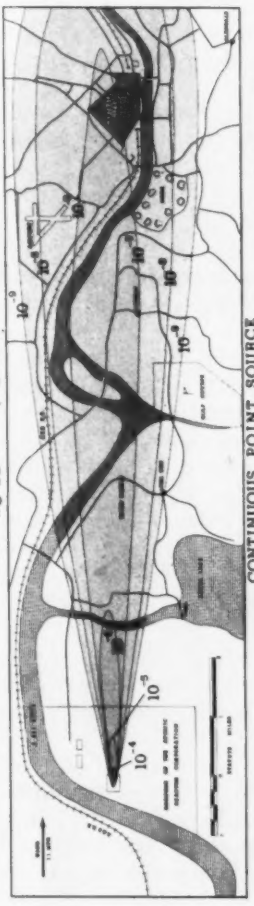
Since meteorologists are essentially earthbound in obtaining continuous three dimensional wind measurements (tall towers and meteorological balloons are only partial answers), it has been necessary to utilize indirect measurements of turbulence.

It was early recognized that the vertical temperature structure of the atmosphere was related to the intensity of turbulence, and hence to the rate of diffusion. On clear, sunny days the temperature decreases with height which enables buoyancy forces to continue to carry material upward, or downward, once it has been given a shove by the turbulent wind.

This unstable condition enhances diffusion. On the other hand, on clear nights, at a weather frontal surface, or in certain restricted geographical areas, the temperature may increase with height. When this occurs vertical motion is inhibited. This inversion condition results in slow diffusion.

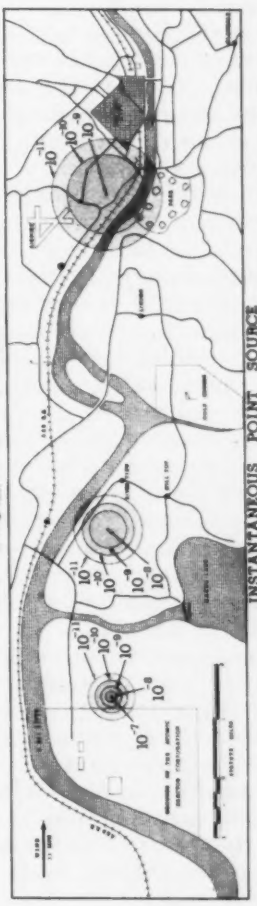
Finally, there is the application of meteorology to the problem of accidental releases of significant amounts of radioactivity. Should such a release occur, the material would travel with the winds and if the activity were sufficient, be of concern tens or even hundreds of miles from the source.

The possible consequences of such accidents have been studied in many reactor hazard reports and in 1957 Brookhaven National Laboratory prepared the report "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Powerplants." From these studies, and from the release of radioactivity at Windscale, England, it is evident that existing weather conditions determine, in a large part, the severity of environmental effects.



CONTINUOUS POINT SOURCE

Surface concentrations for release at ground level, average conditions (wind speed, 11 mph; C^2, 0.033; n, 0.25). Isolines give units of volume concentration (per cubic meter) per unit source strength (grams per second, curies per second, etc.) for a continuous point source.



INSTANTANEOUS POINT SOURCE

Successive instantaneous surface concentration patterns from a release at 50 meters, average conditions (wind speed, 11 mph; C^2, 0.02; n, 0.25). Isolines give instantaneous volume concentrations (per cubic meter) per unit source strength (grams, curies, etc.) at about 8 min, 23 min, and 53 min, respectively from time of release.

FIG. 2 IDEALIZED ATMOSPHERIC DIFFUSION PATTERNS

For this reason all meteorological groups working in this field are studying this problem and most have plans for providing, on short notice, estimates of the direction and distance of travel of any accidentally released radioactivity.

In addition, the Weather Bureau has begun a study of the results of releasing small amounts of radioactivity from a large number of nuclear sites relatively close together. The purpose of this study is to assess the effect of various weather patterns on the possible interaction between sites.

Studies by the meteorological groups working directly with the Atomic Energy Commission have been augmented by theoretical and engineering research by meteorologists at various universities, industrial installations and governmental laboratories.

The results of the major studies have been made available through the meteorological literature and have guided and influenced subsequent investigations. Figure 3 illustrates a field experiment using smoke as an atmosphere tracer and shows a few of the Weather Bureau research studies on diffusion.

While the existing theories and engineering applications of meteorology to nuclear science are useful and valuable, there are many areas in which our knowledge is insufficient. We need to develop a nationwide climatology of diffusion. We need to know how to predict the diffusion potential of new areas utilizing only gross weather data and topographical information.

We must determine how to relate, quantitatively, measurements of basic weather parameters, solar radiation for example, to the intensity of turbulence. Improved theory and observations are needed to estimate diffusion over long distances and in irregular terrain.

Figure 4 shows the location of Weather Bureau research teams currently working on these problems.

The accomplishment of these goals will take time and effort but successful completion will increase our ability to utilize the atmosphere for the safe and efficient disposal of radioactivity and will improve our understanding of all industrial air pollution problems.

Representative HOLIFIELD. Thank you, Mr. Pack.

Are there any questions from the committee?

Chairman DURHAM. I would like to ask you one question, Mr. Pack. Did you get any information out of the Windscale investigation so far as your department is concerned?

Mr. PACK. Yes, sir, we have.

We prepared for the Atomic Energy Commission a meteorological analysis of the situation and in very recent weeks the British have published a number of environmental measurements, particularly in England, that are related to dispersion by the atmosphere. It has been very useful.

Chairman DURHAM. All of that is available for us to use?

Mr. PACK. Yes, sir, it is.

Representative HOLIFIELD. Thank you, sir.

(Mr. Pack's formal statement follows:)

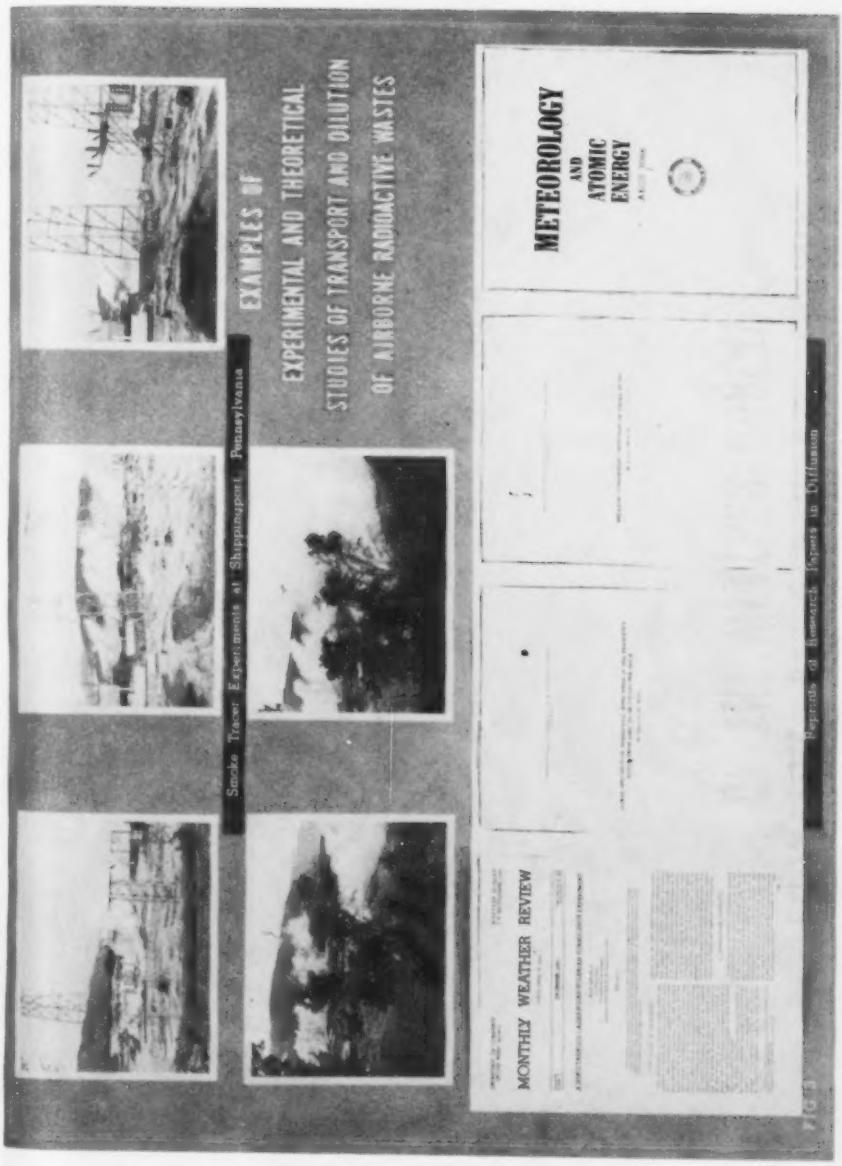

EXAMPLES OF
EXPERIMENTAL AND THEORETICAL
STUDIES OF TRANSPORT AND DILUTION
OF AIRBORNE RADIOACTIVE WASTES
Smoke Tracer Experiments at Shippingport, Pennsylvania
MONTHLY WEATHER REVIEW
METEOROLOGY
AND
ATOMIC
ENERGY
Reprints of Research Papers in Diffusion

FIGURE 3

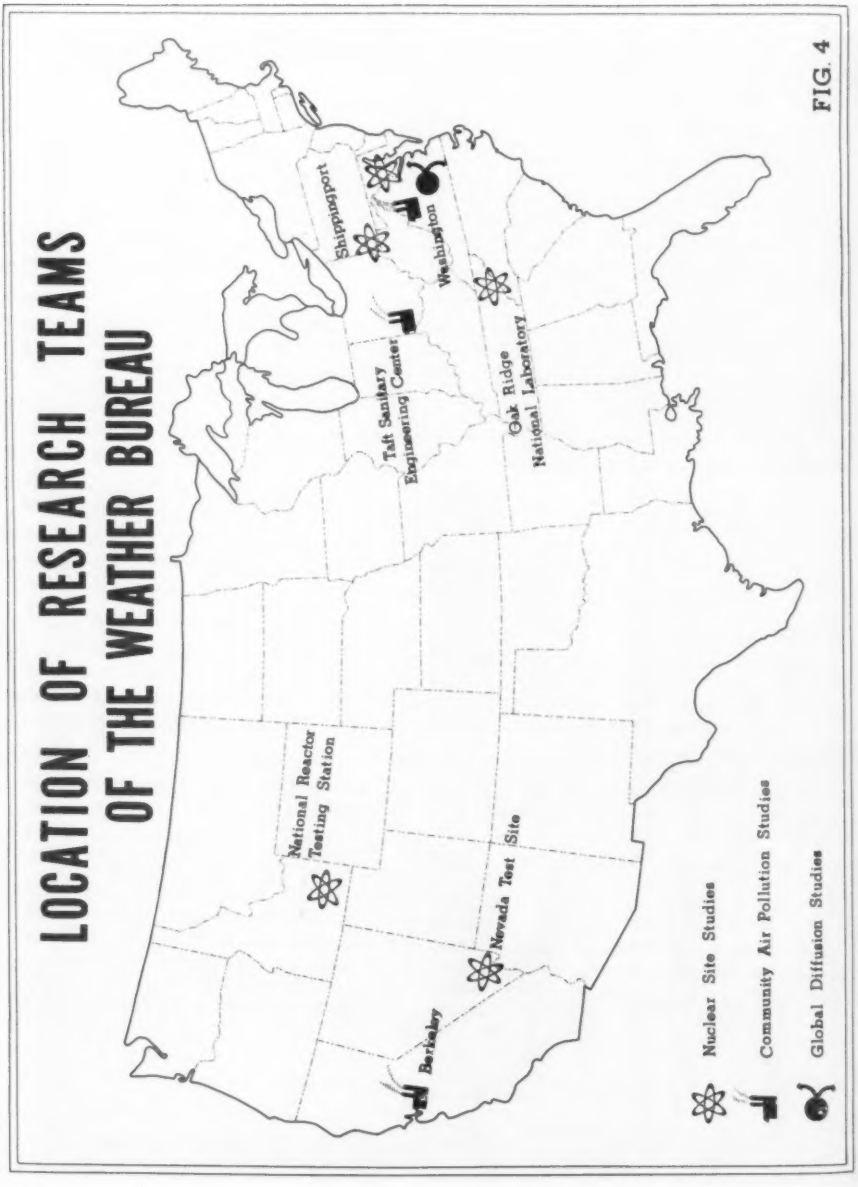

LOCATION OF RESEARCH TEAMS
OF THE WEATHER BUREAU
Shippingport
Washington
Taft Sanitary
Engineering Center
Oak Ridge
National Laboratory
National Reactor
Testing Station
Nevada Test Site
Berkeley
Nuclear Site Studies
Community Air Pollution Studies
Global Diffusion Studies

FIG. 4

Statement of Donald H. Pack
Meteorologist, Department of Commerce,
Weather Bureau

The atmosphere is the most mobile of all geophysical media. It can carry material for great distances in relatively short times, crossing geophysical and political boundaries without pause or interruption. The atmosphere is also an effective dispersing agent and can dilute gases and small particles through a tremendous volume in a relatively short time. In addition, the action of precipitation, and turbulence near the ground, tend to constantly cleanse the air and remove foreign material.

Because of these characteristics of the air its effective use in the disposal of some forms of radioactivity aids in the efficient and economic application of nuclear energy. However it has also been the goal to develop the field of nuclear energy so that its effect on the environment is safely neglible. To do this we must understand the environment; in this case we must understand the meteorological variations that control the transport and dilution of material in the air.

There are large variations in the capacity of the atmosphere to disperse radioactivity or any other pollutant. The effects of lakes and mountains, daylight and darkness, winter and summer on the flow of air and its diffusive capacity must be quantitatively measured and then interpreted in terms applicable to the operation of specific nuclear plants.

The study of atmospheric diffusion is not uniquely related to the nuclear energy industry. Early investigations, particularly in England, were directed towards understanding the dispersion of chemical smokes and agents and to the assessment of effects of industrial air pollution. We were thus able to begin our study of the diffusion of radioactivity with an operational theory available for use(1).

The problem facing the meteorologist is to measure and interpret weather observations in terms of three areas of application.

First is site selection and analysis. When a location for a nuclear plant is being chosen it is desirable to compare, along with other physical and economic criteria, the atmospheric transport and dilution potential of several possible sites. The wind direction frequencies are determined, and related to population distribution; the frequency and persistence of "rapid" and "slow" diffusion periods are examined; precipitation amounts, frequency and concurrent winds are studied; the possibility of local wind channeling or other anomalies is determined. These and other factors are combined into a site climatology

FIG. 4
Global Diffusion Studies

which, when related to the planned nuclear devices, permit inter-comparison of various sites. If however, only a single location is under consideration, a similar meteorological analysis provides valuable design criteria. That is, from the meteorological analysis, it is possible to determine how much more (or less) engineering effort must go into the design of containment vessels, gaseous waste disposal equipment etc. Many analyses of this type have been made by the Weather Bureau and by other meteorologists. Several such surveys by the Weather Bureau have been listed in Appendix I of this statement but one of the most comprehensive was "A Micrometeorological Survey of the Oak Ridge Area — ORO-99"[2] prepared by the Weather Bureau to summarize our studies in that area.

Secondly the meteorologist may then be required to determine when atmospheric conditions are favorable for the operation of various nuclear devices and even, particularly in the last few years, to forecast the occurrence and duration of such conditions. Pioneering work in this field was carried out at Brookhaven National Laboratory where the air cooled graphite reactor operated under "meteorological control" (that is operations were tailored to fit the weather) for several years. More recently the Weather Bureau Office at the National Reactor Testing Station has provided meteorological advice and forecasts for various operations including the Chemical Processing Plant, Aircraft Nuclear Propulsion experiment, certain reactor tests at the Special Power Excursion Reactor Test facility and for other special one-time experiments. This work consists essentially of observing parameters related to the dilution potential of the atmosphere, and wind speed and direction, then forecasting the expected character of the atmosphere.

It is, of course, easier to describe what must be done than to do it. Qualitatively the concept of diffusion in the atmosphere is not particularly difficult. Observation of the spreading of smoke plumes shows agreement with our intuitive idea of what should take place. In a plume of smoke the material is relatively concentrated near the central portion and the concentrations decrease towards the edge of the plume and diminish with time or distance from the source. The cause of this decrease in concentration is the wind, which carries the material along and stretches it out so to speak and also, due to vertical and horizontal movements, disperses the material through an ever greater volume. Because of our inability to continuously move with and observe a plume of material much research has gone into developing relationships between meteorological measurements at fixed locations and the subsequent diffusion. Oak Ridge[2] and Brookhaven[3] studies demonstrated relationships between fixed point wind measurements made with conventional equipment and atmospheric dilution. Studies by Gifford[4] demonstrated this theoretical relationship between fixed point (Eulerian) wind measurements and those made moving with the wind (Lagrangian).

Since meteorologists are essentially earthbound in obtaining continuous three dimensional wind measurements (tall towers and meteorological balloons are only partial answers) it has been necessary to utilize indirect measurements of turbulence. It was early recognized that the vertical temperature structure of the atmosphere was related to the intensity of turbulence, and hence to the rate of diffusion. On clear sunny days the temperature decreases

with height which enables buoyancy forces to continue to carry material upwards (or downwards) once it has been given a "shove" by the turbulent wind. This "unstable" condition enhances diffusion. On the other hand on clear nights, at a weather frontal surface, or in certain restricted geographical areas the temperature may increase with height. When this occurs vertical motion is inhibited. This "inversion" condition results in slow diffusion. Most meteorologists agree that present theory, when adjusted to include parameters appropriate to specific locations, will provide reasonable estimates of diffusion out to distances of (at most) a few tens of miles during unstable conditions. Quantitative assessment of inversion diffusion on the other hand is only now beginning to yield to research[5,6,7].

Results of research and development to the present time have shown us how to measure wind and temperature gradients in a manner suitable for diffusion studies. Automatic weather networks have been developed[8] to permit remote measurements at numerous locations; these are automatically transmitted to central collecting points and in many instances summarized and analyzed by high speed computers. This development was made necessary by the vast amount of data required for diffusion studies. The number of hourly wind measurements collected from a network of say ten stations would total more than 85,000 observations per year, and these represent only a fraction of the information collected.

From these wind and temperature gradient data we can determine diffusion coefficients appropriate to the various locations and to assess the variation of these parameters with season, time of day and, to a degree, with large scale weather variations.

One of the most useful tools in studying diffusion has been the release of tracer materials to the air and sampling of the resulting dilution. The difficulty of such a method is that a full scale tracer study requires tens, or even hundreds of sampling points and many repetitions of the experiment to encompass a variety of weather patterns. These special tracer experiments are necessary for many investigations in which the place, time and amount of tracer release must be controlled. However for some purposes, the small amounts of radioactivity emitted from routine processes can be used as a tracer. The extreme sensitivity of radiological measuring equipment and the existence of established networks of this equipment at many nuclear sites often makes it possible to use this radioactivity as a meteorological tracer with only minor additional equipment and manpower. This technique has been used extensively by the Weather Bureau at the National Reactor Testing Station.

When all these measurements have been taken, correlated, and studied, we are then ready to try to predict future diffusion conditions. This requires relating small scale weather patterns with cloud conditions, pressure patterns, to rain and all other weather factors. In some locations and under carefully selected conditions this forecasting has been remarkably successful and useful but much remains to be studied and understood.

Finally, there is the application of meteorology to the problem of accidental releases of significant amounts of radioactivity. Should such a

release occur the material would travel with the winds and if the activity were sufficient, be of concern tens or even hundreds of miles from the source. The possible consequences of such accidents have been studied in many reactor hazard reports and in 1957 Brookhaven National Laboratory prepared the report "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants"(9). From these studies, and from the recent release of radioactivity at Windscale, England (the Weather Bureau prepared a post-analysis of the trajectories of the radioactivity from Windscale for the Atomic Energy Commission) it is evident that existing weather conditions determine, in a large part, the severity of environmental effects. For this reason all meteorological groups working in this field are studying this problem and most have plans for providing on short notice estimates of the direction and distance of travel of any accidentally released radioactivity. In addition the Weather Bureau has begun a study of the results of releasing small amounts of radioactivity from a large number of nuclear sites relatively close together. The purpose of this study is to assess the effect of various weather patterns on the possible interaction between sites.

Studies by the meteorological groups working directly with the Atomic Energy Commission have been augmented by theoretical and engineering research by meteorologists at various universities, industrial installations and governmental laboratories. The results of the major studies have been made available through the meteorological literature and have guided and influenced subsequent investigations. There have been numerous meetings and visits between the meteorologists at the various Atomic Energy Commission locations so that each program has benefited by research at other locations.

Much of what was known of the techniques for application of meteorological information to atmospheric dilution of radioactivity was summarized by the Weather Bureau for the Atomic Energy Commission in the publication "Meteorology and Atomic Energy", ~~copy attached~~. Additional Weather Bureau studies are listed in Appendix I and copies of our research summary reports over the past three years are reproduced in Appendix II.

While the existing theories and engineering applications of meteorology to nuclear science are useful and valuable there are many areas in which our knowledge is insufficient. We need to develop a nation wide climatology of diffusion. We need to know how to predict the diffusion potential of new areas utilizing only gross weather data and topographical information. We must determine how to relate, quantitatively, measurements of basic weather parameters, solar radiation for example, to the intensity of turbulence. Improved theory and observations are needed to estimate diffusion over long distances and in irregular terrain.

The accomplishment of these goals will take time and effort but successful completion will increase our ability to utilize the atmosphere for the safe and efficient disposal of radioactivity and will improve our understanding of all industrial air pollution problems.

REFERENCES

1. Sutton, O. G., "A Theory of Eddy Diffusion in the Atmosphere", Proc. Roy. Soc. (London), 135A: 143 (1932).

2. Holland, J. Z., "A Meteorological Survey of the Oak Ridge Area", AEC, ORO-99, (November 1953).

3. Smith, M. E., "The Forecasting of Meteorological Variables", Meteorol. Monographs, 1 (4): 50-55 (1951).

4. Gifford, F., "A Simultaneous Lagrangian-Eulerian Turbulence Experiment", Monthly Weather Review 83 (12): 293-301, (December 1955).

5. Hilst, G. R., "The Dispersion of Stack Gases in Stable Atmospheres", Jour. of APCA, Vol. 7, No. 3, (November 1957).

6. Smith, M. E.; Singer, I.; Bartlett, F. E., and Marcus, L., "The Variation of Effluent Concentrations during Temperature Inversions", Jour. of APCA, Vol. 7, No. 3, (November 1957).

7. Cramer, H. E., "A Practical Method for Estimating Dispersal of Atmospheric Contaminants" (paper presented at the First National Conference on Applied Meteorology, AMS, Hartford, Connecticut, October 1957).

8. Myers, R. F., "A Low-Level Temperature Sounding for Routine Use", Bulleten AMS 33 (1): 7 (1952).

9. Atomic Energy Commission, WASH-740, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants", (March 1957).

APPENDIX I

Selected Publications and Research Papers

A. Publications

1. Eisenbud, M., and Wanta, R. C., "Non-Occupational Berylliosis", AEC, NYOO-53, March 1949.
2. Gifford, F. G., Jr., "An Alignment Chart for Double Theodolite Computations", Mon. Wea. Rev. 80, 1952.
3. ———, "A Study of Low-Level Air Trajectories at Oak Ridge", Mon. Wea. Rev. 81, 1953.
4. ———, "An Alignment Chart for Atmospheric Diffusion Calculations", Bulletin AMS, March 1953.
5. ———, "The Height of Scintillation Producing Disturbances", Bulletin AMS 36, 1955.
6. ———, "Atmospheric Diffusion from Volume Sources", Jour. AMS, June 1955.
7. ———, "A Simultaneous Lagrangian-Eulerian Turbulence Experiment", Mon. Wea. Rev., December 1955.
8. ———, "The Relation Between Space and Time Correlations in the Atmosphere", Jour. AMS 13, 1956.
9. ———, "An Atmospheric Diffusion Nomogram with Extended Parameter Ranges", ORO-149, Oak Ridge, February 1956.
10. ———, "Relative Atmospheric Diffusion of Smoke Puffs", Jour. AMS, October 1957.
11. ———, "Statistical Properties of a Fluctuating Plume Dispersion Model", Atmospheric Pollution Symposium, Oxford, England, August 1958.
12. Griffith, H. L., Panofsky, H. A., and Van der Hoven, I., "Power Spectrum Analysis Over Large Ranges of Frequency", Jour. AMS 13, June 1956.
13. Holland, J. Z., "Time Sections of the Lowest 5000 Feet", Bulletin AMS, January 1952.
14. ———, "A Meteorological Survey of the Oak Ridge Area", ORO-99, Oak Ridge, November 1953.
15. ———, "The Diffusion Problem in Hilly Terrain", Chapter 96 Air Pollution, McGraw-Hill, New York.
16. Humphrey, P. A., and Morgan, D. M., "Procedure for Weighing Fluted Filters with Use of Aluminum-Foil Envelopes", AMA Arch. Indust. Hygiene and Occupational Medicine, May 1953.
17. ———, and Wilkins, E. M., "The Climatology of Stack Gas Diffusion at the NRTS", IDO-10020, Idaho Falls, March 1952.
18. ———, and Wilkins, E. M., "Meteorology of the STR", published in Mark I Feasibility Report WAPD-70, December 1952.
19. ———, and Wilkins, E. M., "Engineering Climatology of the ANP Site, NRTS", IDO-10021, Idaho Falls, April 1953.
20. ———, and Wilkins, E. M., "Diffusion and Engineering Climatology for the Berkeley Radiation Laboratory", U.S.W.B., December 1953.
21. Kleinsasser, T. W., and Wanta, R. C., "The Development of a Forecasting Service for Use in Air Pollution Control", AMA Arch. Indust. Health, October 1956.

22. Machta, L., "Global Scale Dispersion by the Atmosphere", Proc. 2nd U.N. Intern'l Conf. on Peaceful Uses of Atomic Energy, June 1958.
23. McCormick, R. A., "Discussion of Variation of Wind Velocity and Gusts with Height", Proc. ASCE, 79, No. D-126, 1952.
24. ——, "The Partition and Intensity of Eddy Energy at the 91-Meter Level During Unstable Conditions as Observed at Brookhaven National Laboratory", Quart. Jour. Roy. Met. Soc. 80, 1954.
25. Myers, R. F., "A Low-Level Temperature Sounding System for Routine Use", Bulletin AMS, January 1952.
26. ——, and Purdy, D. M., "Dispersion of Airborne Activity and Characteristics of Site", ORNL 1835, Oak Ridge, (undated).
27. Pack, D. H., "An Investigation of the Three-Dimensional Wind Structure Near Shippingport, Pennsylvania", U.S.W.B., Washington, D. C. August 1956.
28. ——, "Meteorology and Reactor Accidents", Proc. Nuc. Energy Training Course for Insurance Personnel, March 1958.
29. ——, "Meteorological Data from Surrounding Stations Supplied for Preliminary Estimate of CANEL Climatology", Section D of Nuclear Physics Hazard Report, PWAC 139, Middletown, Connecticut (undated).
30. ——, and Hosler, C. R., "A Meteorological Study of Potential Atmospheric Contamination from Multiple Nuclear Sites", Proc. 2nd U.N. Intern'l Conf. on Peaceful Uses of Atomic Energy, June 1958.
31. ——, Hosler, C. R., and Harris, T. B., "A Meteorological Survey of the PWR Site at Shippingport, Pennsylvania", U.S.W.B., Washington, D. C., December 1957.
32. ——, Hosler, C. R., and Wilkins, E. M., "Meteorological Analysis Applicable to Operation of a Nuclear Powered Vessel", U.S.W.B., Washington, D. C., 1957.
33. Panofsky, H. A., and McCormick, R. A., "The Vertical Momentum Flux at Brookhaven at 109 Meters", Geoph. Res. Paper No. 19, 1952.
34. ——, and McCormick, R. A., "Properties of Spectra of Atmospheric Turbulence at 100 Meters", Quart. Jour. Roy. Met. Soc. 80, 1954.
35. ——, and Van der Hoven, I., "Spectra and Cross-Spectra of Velocity Components in the Mesometeorological Range", Quart. Jour. Roy. Met. Soc. 81, October 1955.
36. Van der Hoven, I., "Power Spectrum of Horizontal Wind Speed in the Frequency Range from 0.0007 to 900 Cycles Per Hour", Jour. AMS, April 1957.
37. U. S. Weather Bureau, Idaho Falls, Idaho, "A Brief Discussion of the Meteorological Program at the NRTS", IDO-20001, September 1952.
38. ——, "Environmental Aspects of the Materials Testing Reactor Operation", IDO-10016, December 1952.
39. ——, "Tower Observations of Atmospheric Dust", September 1953.
40. ——, "A Meteorological Survey of the CANEL Site, Summer 1956", Bowne, N. E., 1956.
41. ——, "A Meteorological Survey of the CANEL Site, Autumn - Winter, 1956-57", Bowne, N. E., 1957.
42. ——, "Meteorological Aspects of IET Operations", (undated).
43. U. S. Weather Bureau, Oak Ridge, Tennessee, "A Thermistor Temperature Recorder for Meteorological Survey", ORNL-556, May 1950.
44. U. S. Weather Bureau, Washington, D. C., "Meteorology and Atomic Energy", AECU-3066, July 1955.

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45. ——, "Meteorological Aspects of Air Cleaning", September 1953.
46. White, F. D., and Pack, D. H., "Meteorology as Related to Reactor Site Selection", Amer. Soc. of Civ. Eng., July 1955.
47. Wilkins, E. M., "Effects of Topography on Winds and Diffusion Conditions at the NRTS", Jour. APCA, May 1956.
48. ——, "A Discontinuity Surface Produced by Topographic Winds Over the Upper Snake River Plains, Bulletin AMS, (undated).

B. Research Papers (U. S. Weather Bureau)

1. "Climatological and Atmospheric Diffusion Study for Dayton, Ohio", June 21, 1948.
2. "Wind Roses for Stations in the Oak Ridge Area", October 12, 1948.
3. "Climatological Report for Fort Peck, Montana; Pierre, South Dakota and Wilmington, North Carolina", November 29, 1948.
4. "Climatological Report for North Platte, Nebraska; La Junta, Colorado; and Kalamath Falls, Oregon; Supplement No. 1", December 23, 1948.
5. "Recommended Meteorological Requirements of the AEC Nuclear Reactor Test Site, ARCO, Idaho", September 16, 1949.
6. "Preliminary Climatological Report for Site 5 (South Carolina) and Site 129 (Illinois)", October 20, 1950.
7. "The Fumigation Index", November 27, 1950.
8. "Meteorological Aspects of the Knolls Atomic Power Laboratory Site", 1951.
9. "The Critical Richardson Number in an Elevated Layer Near Sunrise", Wanta, R. C., (undated).
10. "Some Measurements of Vertical Diffusion in the Free Atmosphere", January 1951.
11. "Formulae for Estimating Concentrations and Exposures from Radioactive Stack Gases", January 28, 1951.
12. "Effects of Meteorological Elements on Radium Emanation from the Soil", April 12, 1951.
13. "Meteorological Effects on Dispersion of ARE Airborne Wastes", June 5, 1951 (also ORNL 1407).
14. "Winds in the Vicinity of X-10 Correlated with Thermal Stability and Precipitation", (undated).
15. "Meteorological Estimates for Rocky Flats Plant of the AEC", July 27, 1951.
16. "Meteorological Aspects of the Proposed SIR Site at West Milton, New York", October 1951.
17. "Expected Meteorological Conditions for the Weldon Springs Site of the AEC", November 1951.
18. "Area Climatological Summary", 1952.
19. "The Development of a Digital Telemeter System", Myers, R. F., 1952.
20. "Expected Meteorological Conditions for the Livermore Research Laboratory of the AEC", May 1952.
21. "Tables of Wind Direction, Speed and Stability for Mound Laboratories, and Wind Roses for Several Stations in the Dayton Area", Sept. 30, 1952.
22. "A Review of Meteorology and Possible Atmospheric Waste Disposal Problems at the Lockland, Ohio Site of the AEC", October 1952.
23. "Dispersion of Airborne Wastes in the 7500 Area", October 19, 1952 (also ORNL-1407).

24. "Climatological Data for Tower A-E", October 24, 1952.
25. "Meteorological Estimates for a Fluorine Stack", January 19, 1953.
26. "A Review of Southern New England Weather", April 1953.
27. "Wind Direction Frequencies Pertinent to IET Reactor Location", April 1953.
28. "Climatology and Meteorology of the TSF Site", April 10, 1953.
29. "Estimate of Dispersion of Airborne Activity from the TSF", April 20, 1953.
30. "Difference in Dust Concentrations Between 5 and 15-Ft. Levels in the ANP Area", June 1953.
31. "Sound Propogation Beneath a Temperature Inversion", August 1953.
32. "An Investigation as to the Possibility that Peaks of Particle Densities in July 1953 Were Due to a Source on the NRTS", September 1953.
33. "A Report on a Feasible Meteorological Telemetering System for Oak Ridge, Tennessee", (undated).
34. "Estimates of Ground Concentrations from the 7500 Stack", (undated).
35. "Maximum Ground Concentrations from the 7500 Stack", (undated).
36. "Estimates of Dispersion of Airborne Activity from ORR", 1954 (also ORNL-1794).
37. "Some Characteristics of Medium Scale Turbulence Near 100 Meters at Brookhaven National Laboratory", McCormick, R. A., 1954.
38. "Engineering Climatology for the AEC Portsmouth Area Plant Site", January 29, 1954.
39. "Estimated Ground Concentrations of CPP Effluent After Proposed Increase of Operations", February 1954.
40. "Frequencies of Low Visibilities at Oak Ridge, Paducah and Portsmouth", February 2, 1954.
41. "Frequency and Duration of Periods of Wind Directions Suitable for IET Operations", April 1954.
42. "Notes on Diffusion Conditions Pertinent to Experiments Proposed in ANL-WHZ-373", May 10, 1954.
43. "Meteorology for the Proposed Location of the Army Packaged Power Reactor, Fort Belvoir, Virginia", June 1954.
44. "Calculations for Unit Emissions of Airborne Contaminants", July 1, 1954.
45. "Meteorological Aspects of the Proposed Air Force Engineering Test Reactor WADC, Wright-Patterson AFB", August 1954.
46. "Meteorological Report on the Test Conducted Near the EBR Site", August 1954.
47. "Meteorology for the Proposed Critical Assembly Area Battelle Memorial Institute, Columbus, Ohio", August 1954.
48. "A Comparison of Isolated Mountain Peak and Free Air Temperatures", October 14, 1954.
49. "Dispersion of Airborne Clouds in Melton Valley", November 16, 1954.
50. "An Investigation of Atmospheric Diffusion Using Neutral Balloons", (undated).
51. "Hazards from Airborne Activity", 1955 (also ORNL-1834).
52. "Meteorological Parameters in Waste Disposal", 1955.
53. "On the Form of the Energy Spectrum in the Anistrophic Range", McCormick, R. A., 1955.

54. "On the Variation with Height of Sutton's Diffusion Coefficients in the Boundary Layer", McCormick, R. A., 1955.
55. "Relative Average Annual Ground Concentrations of I^{131} from the ICPP Stack", March 1955.
56. "Estimation of Environmental Hazards of Airborne Radiation from the APPR", June 6, 1955.
57. "Meteorology for a Proposed NACA Nuclear Facility at Sandusky, Ohio", September 1955.
58. "Meteorology for the Proposed Critical Assembly Area, Hartford, Connecticut", September 1955.
59. "Meteorological Conditions Relating to the Location and Height of the ETR Stack", October 4, 1955.
60. "Preliminary Climatological Appraisal of Northeastern Colorado", (undated).
61. "Site Conditions for the Proposed Indian Point Nuclear Steam Electric Station at Indian Point, New York", (undated).
62. "Meteorological Aspects of the Areas Near Belle Meade General Depot, Sharpe General Depot, and New Cumberland General Depot", 1956.
63. "Relations between Eulerian and Lagrangian Turbulence Spectra and Correlations in the Atmosphere", Gifford, F. G., Jr., (abstract published by University Microfilms, Ann Arbor, Michigan, 1956).
64. "Rainfall Averages and Extremes in the Upper TVA Water Shed", January 16, 1956.
65. "Meteorological Information for OMRE", February 28, 1956.
66. "Meteorological Appraisal of the Quehanna, Pennsylvania Site of the Curtis Wright Aircraft Corporation", May 1956.
67. "Wind Velocity Profiles at Brookhaven National Laboratory During Various Lapse Rate Conditions", DeMarrais, G. A., July 2, 1956.
68. "Preliminary Report of Winds on Jackass Flats", August 10, 1956.
69. "Wind Study at the Gravel Gerty Site, NTS", August 17, 1956.
70. "An Experiment to Examine the Confluence of Airflow over the ANP Experimental Site at the NRTS", October 1956.
71. "Meteorological Summary and Recommendations for Proposed Combustion-Engineering Site, Windsor Locks, Connecticut", October 1956.
72. "Meteorology for the Army Ionizing Radiation Center, Sharpe General Depot, Stockton, California", December 1956.
73. "Second Report of Winds on Jackass Flats", December 3, 1956.
74. "Meteorological Conditions at the National Reactor Testing Station", (undated).
75. "Meteorological Report on the Burning Experiment", (undated).
76. "Recent Meteorological Studies for the North End of the National Reactor Testing Station", (undated).
77. "Release of Effluent from the RALA Process", (undated).
78. "Wind Roses for Low Altitudes at Yucca Flat in April", (undated).
79. "A Relay Tester for Eight and Twenty Pin Socket Based DC Operated ReLays", 1957.
80. "Climatological Review for Dawsonville, Georgia", 1957.
81. "Dispersion of Airborne Activity from the Graphite Reactor", 1957.
82. "Dispersion of Airborne Activity from the ORR", Gifford, F. G., Jr.,
83. "Evaporation at the Waste Pit Site", 1957.

84. "Notes on Quantitative Smoke Plume Analysis", 1957.
85. "Turbulent Diffusion in the Atmosphere", Chapter 3, Diffusion of Air Pollution in Industrial Regions, (Report of World Meteorological Organization working group on turbulent diffusion in the atmosphere - to be published), 1957.
86. "Percentage Frequency of Wind Direction, Wind Tower 3", January and February 1957.
87. "400 Area Temperature and Relative Humidity Data", January 4, 1957.
88. "A Simple Relation for Determining Axial Air Concentrations in the Vicinity of Visible Gas Plumes", May 1, 1957.
89. "Percentage Frequency of Days with Persistent Winds by Direction for Wind Station 4, Project 400", July 17, 1957.
90. "Preliminary Climatological Survey of the San Juan, Puerto Rico Area", August 8, 1957.
91. "Summary of 31 Cases in the Study of Atmospheric Turbulence at Brookhaven", Van der Hoven, I., August 12, 1957.
92. "Puerto Rico Hurricanes", August 16, 1957.
93. "Height of Atmospheric Turbulence Layer Under Isothermal Conditions", August 23, 1957.
94. "Proposed Direct Reading Vertical Wind Instruments", Wehmann, G., September 1957.
95. "Average Speed and Directional Change Profiles over NTS", October 1957.
96. "Wind Roses, Dave Hall Reactor Site", November 1957.
97. "Third Report of Winds on Jackass Flats", December 9, 1957.
98. "An Objective Wind Forecast Technique for the National Reactor Testing Station", Mansfield, H. R., (undated).
99. "Comparison of Diffusion Parameters Measured at Other Sites to Those Used at the National Reactor Testing Station", Islitzer, N. F., (undated).
100. "Computation of Sutton-Type Diffusion Coefficients from Visible Limits of Smoke Concentrations", (undated).
101. "Meteorological Control of ETR Air-Cooled Experiments", (undated).
102. "Precipitation Occurrence Recorder", Wehmann, G., (undated).
103. "Progress Report on Investigations of Wind Direction Range and Diffusion Coefficients", Islitzer, N. F., (undated).
104. "Notes on Winds in Area 12", Forecasting guide, (undated).
105. "The Role of Meteorology in Air Pollution", (Submitted to World Health Organization, November 1957).
106. "Diffusion Parameters for NTS", 1958.
107. "Eddies and Circulations in Area 12", 1958.
108. "Inversion and Stability Forecasting", 1957.
109. "Low Level Wind Forecasting", 1958.
110. "Mountain and Valley Winds", 1958.
111. "Reliability of Wind Forecasts at NTS", 1958.
112. "Subsurface Temperature Variation", 1958.
113. "Summary of Weather Conditions in the Oak Ridge Area", 1958.
114. "Weather Forecasting at NTS", 1958.
115. "Wind System Classification", 1958.
116. "A Preliminary Meteorological Analysis of the Windscale Incident", January 1958.

117. "Particle Terminal Velocities in a Fluctuating Atmosphere", Gifford, F. G., Jr., and Culkowski, W. M., March 1958.
118. "Preliminary Consideration of an Objective Forecast Technique for the NRTS", Mansfield, H. R., March 1958.
119. "Preliminary Estimate of Environmental Hazards Associated with the Proposed Puerto Rico Research Reactor", March 4, 1958.
120. "Meteorological Estimates for Portsmouth, New Hampshire and Mare Island, California", April 1958.

APPENDIX II

Research Progress Reports
July 1955 - December 1957

Review of Weather Bureau Meteorological Accomplishments for the Division of Reactor Development Engineering Development Branch U. S. Atomic Energy Commission During Fiscal Year 1956

This is the final report of the Weather Bureau to the Division of Reactor Development, Engineering Development Branch, for meteorological work which they have sponsored during FY 1956.

Washington

Meteorological Services and Investigations

a. The publication "Meteorology and Atomic Energy" was carried to completion through its editorial phases at the Technical Information Service at Oak Ridge, Tennessee.

b. Weather Bureau representatives have visited the following AEC or contractor sites: Shippingport, Hartford, Argonne National Laboratory, Oak Ridge National Laboratory, National Reactor Testing Station, Westinghouse Atomic Power Division, Portsmouth, Ohio, Lockheed Aircraft Corp. (Marietta, Georgia), Convair (Fort Worth, Texas), Quehanna, Pennsylvania, Piqua, Ohio, Cleveland, Ohio and Lockland, Ohio.

c. Meteorological reports were prepared on:

   1. Meteorological Aspects of the Proposed Pratt and Whitney Critical Facility Area.

   2. Meteorological Aspects of Quehanna, Pennsylvania Site.

   3. Additional Remarks on the Meteorology of the Lockheed Site.

d. Meetings of the Advisory Committee on Reactor Safeguards were attended at KAPL and in Washington, D. C. A large number of hazard reports were reviewed in connection with these meetings. In addition external gamma and inhalation radiation dosage curves were computed to provide a comparison of these mechanisms.

e. This office assisted in the activation of a meteorological office for the CANEL site at Middletown, Connecticut. Due to procurement and construction difficulties the data collection program was not fully underway until April 1956.

f. Meteorological advice and/or climatological material has been supplied to numerous groups contemplating the development of nuclear facilities. Some of these were: City of Piqua, Ohio, Foster-Wheeler Corporation, Babcock and Wilcox, to mention a few.

g. The material prepared for the Geneva Conference on the "Peaceful Uses of Atomic Energy" was accepted and included in the conference proceedings; the meteorological exhibit designed by the Weather Bureau was also accepted and included in the U. S. display.

h. The following papers were prepared and presented:

1. "Meteorology as Related to Reactor Site Selection" - presented at the Nuclear Engineering and Science Congress in Cleveland, Ohio and to be published in the "Proceedings of the American Society of Civil Engineers"

2. "Meteorology as Related to Air Cleaning" - presented at the Fourth AEC Air Cleaning Conference at Argonne National Laboratory and included in minutes of the Conference.

3. "Meteorological Parameters in Waste Disposal" - presented at the 1955 Sanitary Engineering Conference at Cincinnati, Ohio.

4. Material for inclusion in the first report of the National Academy of Science Committee on the "Meteorological Aspects of the Biological Effects of Atomic Radiation".

i. A meeting was held in November of all the supervising meteorologists at the various Atomic Energy installations where the Weather Bureau has personnel assigned.

Brookhaven

Mr. R. A. McCormick, the former Meteorologist in Charge, was assigned at Weather Bureau expense, to the British Meteorological Office for a tour of approximately one year's duration. He was replaced by Dr. Isaac Van der Hoven. The research program conducted during this year was as follows:

a. Research Projects - Investigation of the basic structure of turbulence and its influence on air pollution concentrations as follows:

1. Variations in the spectrum of turbulence: The "Solar day" analysis is nearing completion and plans are complete for sampling a "Non-Solar day".

2. Space and Time Distribution of Eddy Energy: Additional information is being collected and analyzed. Preliminary results seem to show that the high frequency is correlated with wind speed at low levels.

3. Smoke Concentrations from 355-foot Stack: Data collection halted during inclement weather. Experiments resumed during Spring. An analysis of limited data by Gifford shows better agreement with Sutton's formulation.

4. Further Evaluations of Sutton Formula Coefficients: Study continuing. Limited data show a small decrease of these coefficients with height between 23 and 91 meters.

5. Horizontal Spectral Gap: Additional data from locations other than Brookhaven are being analyzed.

6. Neutral Balloon Experiments: Experimental program to be completed by June 1956.

b. Meetings, Papers and Talks

1. "Power Spectrum of Wind Speed in the Mesometeorological Range", Panofsky and Van der Hoven, presented at the 139th National Meeting of the American Meteorological Society.

2. "Spectra and Cross Spectra of Velocity Components in the Mesometeorological Range", Panofsky and Van der Hoven, published in the Quarterly Journal of the Royal Meteorology, October 1955.

3. "Effects of Scale in Atmospheric Turbulence", presented at an air pollution course given by the Institute of Industrial Medicine Postgraduate Medical School of New York University.

Shippingport, Pennsylvania

a. Observational Services - The observational program of collecting data for all of the standard meteorological parameters, as well as temperature gradient measurements, has continued smoothly. The instrumental malfunctions which disrupted some of the early record have been largely overcome and little difficulty is now experienced in this field. In addition to the unquestioned value of these data for air pollution site evaluation the information collected has proved useful to the contractors working at the site for protection of pouring concrete, earth moving, work scheduling, etc.

b. Site Services - A daily forecast is furnished to various offices on the site and a warning service for hazardous weather conditions has been established. At the request of Dr. Sidney Krasik the data which had been collected and summarized through October was supplied to WAPD for inclusion in a hazard analysis for the PWR. These data show the location to be quite unfavorable because of the high frequency of the inversion conditions. This was not unexpected.

Middletown, Connecticut

Development of this program progressed to the point where the first Weather Bureau personnel were assigned in October to assist in developing the program, extending the specifications for the instrumental equipment and site layout, and to further develop local climatological data prior to beginning of the observational program. Mr. Norman E. Bowne the Meteorologist in Charge reported for duty at Oak Ridge, Tennessee for a period of indoctrination and training and was then assigned to the Middletown site in December. The Weather Bureau Office moved from their location with the Fox Project in East Hartford to the actual CANEL site near Middletown in December. Portable anemometer equipment was installed on that date and the meteorological record begun with the scanty equipment on hand. Procurement difficulties delayed the remainder of the meteorological equipment as well as the erection of the tower. However, all of the equipment has been received and is now in service, and data analysis for several months has been obtained.

Idaho Falls, Idaho

The expansion of activities, particularly the Aircraft Nuclear Propulsion program, has required a corresponding increase in meteorological demands on this office.

a. Research Projects

1. Studies of the standard deviation of the wind direction fluctuations under various conditions, and the computation of diffusion coefficients based on this parameter have been continued.

2. Diffusion experiments using fluorescent powder were conducted. The tracer was released under operating conditions through the IET stack. Reduction of the filter data obtained on these initial tests is not yet complete.

3. Preliminary engineering studies and much developmental planning on the combination bivane-anemometer for direct indication and recording of vertical wind speed has been completed. Plans are sufficiently far along so that construction of this equipment can probably start before the end of this fiscal year.

4. Further intensive studies are being made of the local winds over the NRTS, partially to assist in the forecasting of these winds for operational programs, but basically to determine the role of these winds in the transport of effluent. This program involves synoptic-scale as well as micro-scale studies.

5. The depth of and persistence of inversions are being studied in relation to various parameters in an attempt to provide guides for forecasting the characteristics of this phenomenon.

6. Began an investigation of local wind conditions in the vicinity of the proposed operational runway at the north end of the NRTS. First results seem to indicate no serious aircraft hazard exists due to wind shifts along the proposed runway.

7. A densitometer was constructed to be used in an attempt to evaluate quantitatively the dust collected on filters used for radiological monitoring. It is hoped that a relationship can be obtained between the light transmission through these filters after exposure and the dust in the atmosphere as determined by weighing MSA fluted filters.

b. Reports

1. "Relative Concentrations of Stack Effluents under Looping and Fumigation Conditions". Prepared for the Director, IDO Health and Safety Division for the study of the feasibility of various locations for the ETR.

2. "Meteorological Considerations for the Location of the ORME". Prepared for the Director, IDO Health and Safety Division.

3. "Meteorological Conditions at the NRTS during the period 15-22 May 1955". Prepared for inclusion with a report by the Chief, IDO Site Survey Branch on the radiological monitoring conditions during the same period.

4. "Meteorological Problems in the Location and Operation of Reactors". A talk presented before the Second Annual Nuclear Sciences Seminar sponsored by the Office of Naval Research.

5. "Meteorological Conditions at the NRTS". Prepared for transmittal to North American Aviation Corporation by the Contract Administration Branch, IDO.

6. "Meteorological Considerations Relating to the Location and Height of the ETR Stack". Memorandum report prepared for the Director, IDO Health and Safety Division.

7. "Meteorological Control of ETR Air-Cooled Experiments". Prepared for transmittal to Phillips Petroleum Company by the Director, Health and Safety Division, IDO.

8. "Release of Effluent from the RALA Process". Prepared for inclusion in the minutes of a meeting of Site Representatives for Discussing RALA Processing.

c. Site Services

1. The Weather Bureau has furnished advice to the Site Survey Branch of IDO Division of Health and Safety on:

   a) Location of radiological monitoring stations for the telemetering system north of the NRTS.

   b) Location of radiological monitoring station on the NRTS to detect the continuous effluent from the MTR.

   c) Location of radiological monitoring stations for the permanent network covering the Snake River Valley.

   d) Direction of mobile monitoring during periods of hazardous operations.

2. The furnishing and interpretation of weather forecasts for the AEC and its contractors has continued. Fire Weather Forecasts (winds and humidity) were made on a daily basis throughout the summer; strong wind forecasts are made for the Safety Branch for control of construction activities; temperature forecasts for concrete pouring are made at the request of construction contractors; routine temperature forecasts are given to the CPP boiler room to assist in preparing for heat demands; general weather forecasts of severe weather are given to the transportation division and to the State and County road departments.

3. Special tabulations of climatological data were prepared for the IDO Division of Engineering and Construction for use by contractors in designing ETR and LSR, and recommendations as to exhaust stack height and location were made for both on these sites.

4. Beginning in late December 1955 daily forecasts of diffusion parameters have been prepared for use by contractors in evaluating on a current basis hazards associated with specific reactor operations.

d. Instrumentation

1. A telemetering system for relaying weather data from the tower at the north end of the NRTS to the Weather Bureau Office at Central Facilities Area was procured by General Electric Company and installed by a representative of the manufacturer, General Electric Company and Weather Bureau personnel. Wind speed and direction at four levels and temperature at seven levels are provided by this system.

2. Six micrometeorological stations have been maintained during the year.

Fort Worth, Texas

The primary activity of this office is to maintain liaison with the Convair Aircraft Nuclear Propulsion program and to participate in the development of a philosophy regarding the operations of nuclear powered aircraft. Specifically the meteorological requirement is to develop criteria bearing on the safe and efficient usage of such aircraft.

a. Research

1. Development of meteorological criteria for nuclear aircraft operation.

2. Observations of oil smoke behavior.

3. Diffusion measurements using a "smoke puffer": Computations of diffusion coefficients for an instantaneous source have been made and are being extended.

4. Preliminary investigation of tracer feasibility of Argon 41 using crystal scintillometers as counters.

b. Site Services

1. Preparation of meteorological and dosage calculations for reactor hazard calculations: These include the ASTR, REF, and NTA operations manual.

2. Provide instruction for Convair personnel in significance and applications of meteorology to nuclear operations: Several lectures on this subject have been presented.

3. Collection of meteorological data pertinent to diffusion in the Carswell area: A meteorological tower is now nearing completion.

4. Special forecasts and briefings for certain flight operations.

c. Meetings, Talks and Papers

1. "Topographic Effects on Winds and Diffusion Conditions over the NRTS" presented at the APCA meeting in Detroit, Michigan.

2. "Current Methods of Determining Reactor Environmental Hazards", lecture to Convair personnel.

3. "Micrometeorological Aspects of Reactor Hazards Analysis", lecture to Convair personnel.

4. "Computation of Atmospheric Diffusion Coefficients from Smoke Puff Experiments".

WEATHER BUREAU PROGRAM FOR THE ENGINEERING DEVELOPMENT BRANCH, REACTOR DEVELOPMENT DIVISION, U. S. ATOMIC ENERGY COMMISSION

Mid-Year Review - July-December 1956

Brookhaven

Resume

a. Research - The following projects were pursued:

1) Spectrum of horizontal wind speed between periods of 1000 hours and 4 seconds - The program to test the generality of the existence of a significant gap in the spectrum of horizontal wind speed has developed into a determination of the spectrum over a frequency range from 7×10^{-4} to 9×10^{2} cycles per hour. Spectra were computed for combined data from Oak Ridge, Idaho Falls, and Brookhaven. This representative spectrum showed two major eddy energy contributions, one peak occurring at a period of about 4 days and the second at a period of about 1 minute.

2) Relationship between the spectrum of turbulence and mean parameters - Sufficient spectra have been collected to relate eddy energy to various meteorological parameters such as wind speed, solar radiation, vertical temperature gradient, vertical wind gradient and height above the ground.

3) Wind profile between 11 and 125 meter height - Summarized data showed a relationship between mean wind speed profiles and temperature lapse rate at Brookhaven with the wind profile decreasing in slope with decreasing stability, approaching a constant slope when super adiabatic conditions are reached.

4) Evaluation of Sutton's diffusion coefficients - Evaluation of the coefficients C_y, C_z, and n using meteorological parameters such as wind profile, stress and eddy energy is in agreement with the work at Oak Ridge, the Massachusetts Institute of Technology, etc. in that the values are higher than those of Sutton's under similar stability conditions.

5) Lagrangian-Eulerian correlations - This office, together with the Weather Bureau Office, Oak Ridge; Pennsylvania State University; and Woods Hole Oceanographic Institution co-operated in measurements of Lagrangian velocity spectra from neutral balloons, Eulerian time spectra from tower data and stress and velocity measurements from a low-flying aircraft.

b. Papers

1) "Power Spectrum of Horizontal Wind Speed in the Frequency Range from 7×10^{-4} to 9×10^{2} Cycles per Hour" by I. Van der Hoven - To be published in the Journal of the American Meteorological Society, April 1957.

2) "Wind Velocity Profiles at Brookhaven National Laboratory During Various Temperature Lapse Rate Conditions" by Gerard A. DeMarrais.

c. Talks and Meetings

1) Presentation of paper "Power Spectrum of Horizontal Wind Speed" at the New York meeting.

2) Lecture "Effects of Scale in Atmospheric Turbulence" at an air pollution course sponsored by the Institute of Industrial Medicine, New York University.

3) Lecture "Supplying Weather Stations in the Arctic" to Naval Reserve Unit at Brookhaven National Laboratory.

4) Participation in a meeting at the New York Operations Office regarding the Brookhaven National Laboratory Reactor Hazard Study.

Convair

Resume

a. Research

1) Diffusion coefficients for short time and space intervals were computed by measuring the dimensions and dissipation time of smoke puffs generated from a known amount of gunpowder.

2) An analysis was made on a series of dual neutral balloon runs to determine the rates of horizontal and vertical separation and to compare these data with fixed meteorological observations.

3) A 150 foot meteorological tower was completed and studies begun on inversion anomalies, diffusion climatology and comparison of these data with nearby standard radiosonde ascents.

4) Participation in design of diffusion experiments at Kirtland Air Force Base for dilution of a cloud of material by a low-flying helicopter and in design of simulated crash fires planned for the NRTS.

b. Operations

1) The meteorological portions of reactor hazard analyses were designed and prepared. These included the RER, KTA, SEFR, SASTR, ATF, etc.

2) Meteorological criteria were developed for base selection studies and inter-comparisons on an objective basis.

3) Diffusion forecasts were prepared for special operations of the GTR and NTA.

c. Papers

Papers have been prepared for review and publication on

1) "Computation of Instantaneous Source Diffusion Coefficients from Smoke Puff Observations".

2) "Observations on the Separation Rates of Neutral Balloons and Application to Diffusion Theory".

Dawsonville

Resume - This station was established to assist in the design of a micro-climatological survey and the initial collection of these data. Wind, temperature and precipitation measuring equipment was supplied by the Weather Bureau pending procurement of the necessary instrumentation by Lockheed. Hourly values of these parameters were determined and appropriate summarizations prepared. Qualitative dispersion estimates were obtained from smoke releases. The smoke pots were furnished by the Weather Bureau.

The Weather Bureau meteorologist worked closely with, and received excellent co-operation from, Lockheed meteorologists.

Idaho Falls

Resume

a. Research

1) Studies of atmospheric diffusion utilizing the MTR stack effluent and scintillation counters (sky scanners) developed by IDO as detectors. Measurements at two distances from the source have permitted determination of diffusion coefficients for a limited number of cases.

2) Design and development work on a direct reading and recording vertical wind system has continued.

3) There is a continuing program of study on the relationships between local winds and larger scale weather patterns. As yet, satisfactory parameters for forecasting the development of opposing wind flows over the NRTS have not been obtained.

4) A series of 143 double theodolite balloon runs were made and are now being analyzed.

5) Frequency distributions of wind direction range vs. stability and wind speed for Central Facilities and ANP are being processed by IBM techniques. These data will enable a closer study of the variation of diffusion parameters.

6) Study into the relationship between large scale meteorological situations and the diffusion conditions of the atmosphere continues. The initial findings from this study are utilized to prepare daily forecasts of diffusion. The actual application of these techniques provides a test of, and feedback into, this research.

b. Operations

1) Beginning October 14, operational forecasts of weather conditions and diffusion parameters have been preapred. These are available to IDO and to the various contractors, particularly General Electric. In addition, weather conditions are monitored during specific tests and deviations from forecast conditions reported. Also, the office is responsible for vectoring radio-controlled radiological monitoring units of the IDO Site Survey Branch into appropriate locations during IET tests.

2) A continuing repsonsibility has been assumed for the times of operation, selection of appropriate meteorological conditions, and locations for radiological monitoring teams in connection with ICPP operations. Two such operations were conducted in December with subsequent operations planned at about monthly intervals.

3) The SPERT program is under meteorological control when certain transient periods are being investigated. At these times, determination of appropriate meteorological conditions and positioning of monitoring teams are the responsibility of the Weather Bureau office.

4) Daily forecasts of wind, humidity, and weather were furnished IDO Safety Engineers and the NRTS Fire Department. Temperature forecasts for concrete pouring were prepared during periods of intermittent freezing. Many other requests of this type were answered.

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c. Observational program

1) Meteorological tower data collection continued at Central Facilities together with telemetered recording of the ANP tower data.

2) Sub-surface temperature measurements began November 15.

3) Micro-net stations - Stations continue at Birch Creek, "Y" - midpoint of the proposed runway, near the NRF (plus wind measurements near the spray ponds to determine their efficiency) near the eastern boundary of NRTS, plus telemetered off-site data from Monteview and Comas, utilizing the radiological monitoring telemetering network.

4) Low altitude wind and temperature soundings were taken throughout the period of operational diffusion forecasting.

Middletown

Resume

a. Data collection from the meteorological tower continued without major difficulties. These data are routinely processed and issued monthly, while all data for the summer season has been combined and are being reproduced in report form.

b. Special observations using four portable wind measuring systems have been made at various site locations and correlated with each other and with tower data.

c. Special observations for measurement of inversion heights, vertical motion, and diffusion coefficients were begun using smoke tracers, neutral balloons and a wiresonde system. These observations were made as often as available manpower permitted.

d. Some meteorological advice and data were provided for Combustion Engineering. This resulted from a meeting with Combustion Engineering in October regarding meteorological requirements for their site near Windsor Locks.

Shippingport

Resume

a. The two meteorological stations were kept in continuous operation during the first half of the current fiscal year. At this time, we have twenty-one months of meteorological data. Observed elements have remained unchanged. Some slight modifications have been made in the analysis and recording, but the program remains

fundamentally the same. Annual wind roses have been drawn and the frequency of inversions by hours has been tabulated.

b. A daily forecast is furnished to three offices of Burns & Roe, Inc., agent constructor for the Duquesne Light Company and two copies to the Dravo Corporation, sub-contractor for the Westinghouse Corporation. The five-day outlook is included on each of these forecasts on Monday, Wednesday, and Friday. Minimum temperature forecasts are again becoming increasingly important with the advent of colder weather as concrete pouring is still in progress.

c. The Industrial Hygiene group at Westinghouse Corporation has requested, and is receiving, copies of the daily weather observations. They are using this data in connection with their air monitoring program.

d. The Pressurized Water Reactor Physics group of Westinghouse requested and received numerous wind frequency data and a one-year summarization of inversion frequencies by hours.

e. At the request of the Atomic Energy Commission, an experiment to investigate the three-dimensional wind flow in the vicinity of the Pressurized Water Reactor Site was performed August 20-26, 1956. Using meteorological balloons and smoke as tracers, the vertical velocities and trajectories of the air currents in the area were measured. The Office of Meteorological Research, U. S. Weather Bureau, directed the experiment and prepared a report entitled "An Investigation of the Three-Dimensional Wind Structure near Shippingport, Pennsylvania".

Washington

Resume

a. Research

A project to measure the three-dimensional wind structure during stable atmospheric conditions was completed during August at the site of the PWR at Shippingport, Pennsylvania. A report of this work was furnished your office for distribution to the interested agencies.

b. Meteorological services and investigations

1) Weather Bureau representatives have visited the following AEC or contractor sites: Shippingport, Middletown, Dawsonville, Idaho Falls, Combustion Engineering, and Brookhaven.

2) Meteorological reports were prepared on:

   a) Comparative Site Evaluation for the Army Ionizing Reactor.

   b) Meteorological aspects of the Sharpe General Depot, Stockton, California.

3) Two meetings of the Advisory Committee on Reactor Safeguards were attended in Washington. In addition to the review of the reports for these meetings, special attention was given to the meteorological aspects and requirements for the PRDC reactor.

4) Weather Bureau representatives met with the Meteorology Group of Brookhaven National Laboratory to discuss the planning of the meteorological portion of the Reactor Hazards Evaluation and later participated in the review of the first draft of the complete study. Comments and suggestions resulting from the meeting were forwarded to BNL and to the Reactor Hazards Evaluation Staff.

5) Meteorological advice and/or climatological information has been furnished to numerous groups interested in the nuclear energy field including Walter Kidde, Martin Aircraft, Curtiss-Wright, and others.

6) We were visited by Dr. Paul Courvoisier of Switzerland and Dr. Toshio Aoki of Japan for discussions of the uses of meteorology for nuclear energy. Dr. Courvoisier also visited the Weather Bureau Offices at Brookhaven National Laboratory, Shippingport, Idaho Falls, and Oak Ridge.

7) Material was prepared for a meeting of the World Meteorological Organization "Panel of Experts" on atomic energy in Geneva, Switzerland.

WEATHER BUREAU PROGRAM FOR THE ENGINEERING DEVELOPMENT BRANCH, REACTOR DEVELOPMENT DIVISION, U. S. ATOMIC ENERGY COMMISSION

Review - January-June 1957

and

Highlights - July 1956-June 1957

The Weather Bureau, at the request and with the support of the Atomic Energy Commission, is conducting programs of research and study designed to provide better understanding of the physical parameters governing the transport and dilution of material by the atmosphere. Such information is essential to the calculation of actual or potential concentrations of radioactivity originating from nuclear reactors or fuel processing facilities and contribute materially to an evaluation of the health and safety problems of the nuclear industry.

These programs are assembling information on the basic turbulence mechanisms governing diffusion by the atmosphere; delineating the geographical and topographical variations in microclimate; and developing and testing applications of theoretical and empirical meteorological techniques to nuclear plant design, location, and operation.

Brookhaven

1. Resume

a. Research

1) Spectrum of horizontal wind speed from 10^{-5} to 10^{3} cycles/hour. The program of testing the generality of the various peaks and gaps in the spectrum of horizontal wind speed at about 400-foot height (as reported in Journal of Meteorology, Vol. 14, No. 2, 1957), has been further extended to include the spectrum down to a frequency of 10^{-5} cycles/hour (period of 11 years). This necessitated long-term data not available at Brookhaven. The 47-year wind speed record from Weather Bureau Office, New York City, at a height of 450 feet was used and also the 71-year record from Blue Hill Observatory atop a 600-foot hill with the instrument 52 feet above the ground. This was considered representative of the conditions at the 410-foot level of the Brookhaven tower. The two resulting spectra were almost identical and fitted the previously computed spectrum (from 10^{-3} to 10^{3} cycles/hour) very well. The general conclusion is that the major peaks and gaps in the spectrum of horizontal wind speed are included in the frequency range from 10^{-5} to 10^{3} cycles/hour. The two peaks in the spectrum which show the major eddy energy contributions are at a period of about four days and of about one minute. A small peak exists at a period of one year. The major gap in the spectrum is at a period of about one hour.

2) Relationship between turbulence characteristics and mean parameters. The spectra of the velocity components at 91 m for the four alternate hours from 0840-1540, May 5, 1954 have been processed by the Princeton Electronic Computer. The various turbulence parameters such as eddy energy, exchange coefficients of momentum, friction velocity, mixing length, stress, Sutton's C_z, C_y, and n, and the high frequency spectral slope and the various mean parameters such as wind speed, solar radiation, temperature lapse rate, and vertical wind gradient have been computed and tabulated.

3) Wind profile between 11 and 125 m height. Wind direction data were sent to Mr. DeMarrais at Pennsylvania State University, for his Master's thesis on the relationship between wind profile and the temperature lapse rate. The study was started by DeMarrais while he served as assistant at Upton (see Fiscal Year 1957 mid-year review). A copy of this thesis will be submitted when available.

4) Relationship between Eulerian time and Lagrangian velocity spectra. The tower-measured velocity fluctuations taken during the neutral balloon experiment (see Fiscal Year 1957 mid-year review) have been analyzed to obtain the Eulerian time spectra. These spectra were sent to the Weather Bureau Office, Oak Ridge, Tennessee for comparison with the Lagrangian spectra obtained from neutral balloon fluctuations.

5) Horizontal flux of eddy energy. Using a case where the mean wind direction was along a line between the two Brookhaven meteorological towers (900 feet apart) the mean horizontal flux of eddy energy at 150 feet was evaluated. Five-second mean wind components were taken over an interval of 1/2 hour. The divergence of the horizontal flux of eddy energy between the two towers was found to be -62 $cm^2/sec^2/sec$, thus of the same order of magnitude (10^2) as the divergence of the vertical flux of eddy energy and about an order of magnitude less than the shear and buoyancy terms which are the major contributors to the time rate of change of eddy energy. The conclusion drawn is that neither the divergence of the horizontal or vertical flux of eddy energy serves as an important source or sink of eddy energy.

6) Effect of tower structure on measurement of wind fluctuations. Using two Beckman-Whitley Wind Systems, horizontal wind speed and direction fluctuations were measured at the 18-foot level of the tower. One instrument was placed so that the wind blew through the tower before reaching the instrument, while the other instrument had an unobstructed fetch of wind. Two 1/2-hour cases during windy, unstable conditions using 5-second means were used. The only consistent result showed a 10% reduction in mean wind speed due to the wind blowing through

the tower. The cross wind (v-component) and mean wind (u-component) also consistently showed a reduction because of the tower effect, but the amount varied from 6 to 35%. It would seem then that if the tower causes any turbulence in the wind, it is of such a high frequency that the instrumentation used could not measure the fluctuations. It also seems that the tower has the effect of smoothing out the low frequency fluctuations much as a grid in a wind tunnel does. However, the apparent decrease of σ_u^2 and σ_v^2 with the wind blowing through the tower may be largely due to the decrease in mean wind speed.

7) Onset of turbulence. A study was initiated to determine the mechanism by which the turbulence started at the surface by solar heating was propagated upward. Using the rationale stated by Machta in "A Proposed Meteorological Air Pollution Index", a simple model was used whereby the eddy energy created by the vertical wind fluctuations was equated to the energy required to overcome the downward buoyancy force. The resulting equation was

$$h = c\,\bar{v}_{sfc}\left(\frac{T}{g}\right)^{1/2}\left[\gamma - \Gamma\right]^{-1/2}$$

where h is the depth of the turbulent layer, $\bar{v}_{sfc}$ the surface wind speed, T the mean temperature of the layer, g the acceleration of gravity, γ and Γ the existing and adiabatic temperature lapse rates, respectively, and c is a constant relating eddy energy to mean wind speed. Measurements from the 410-foot tower made it possible to measure the parameters and so empirically determine the constant. It was difficult to decide on the mean lapse rate for the turbulent layer. Consequently, the point at which isothermal conditions existed was used since this point could be more easily identified. Results in the determination of the constant were quite disappointing, varying from 1.0 to 5.0 for 20 isothermal cases. The conclusion thus far is that the model used is too simple and does not account for the stability of the air several hundred feet above the turbulent layer.

2. Highlights

The station's major effort was directed to the analysis of the spectrum of horizontal wind speed. The study is unique in the inclusion of frequencies for such long periods (>10 years).

Dawsonville

1. Resume

   a. Research

      1) Collection and analysis of micro-climatological data continued through May 1957 at which time the meteorologists of the Lockheed Aircraft Corporation assumed responsibility for the station.

      2) Qualitative and semi-quantitative measurements of diffusion were continued with smoke tracers.

      3) Instrumentally determined diffusion coefficients were computed for various meteorological conditions.

2. Highlights

   A final report summarizing the work of the Weather Bureau was prepared and has been previously submitted. Due to the short observational period ($<$ 10 months) the summation cannot be definitive, but it does represent useful information.

Idaho Falls

1. Resume

   a. Research

      1) A literature search has been made to summarize the empirically determined diffusion coefficients (for use with Sutton's formulae) obtained at various locations both in the United States and abroad. It is planned to expand this information and prepare a report for publication.

      2) Additional diffusion coefficients have been obtained using the effluent from the MTR stack as a tracer and sky-scanner scintillation units as detectors. To date, data have been obtained under neutral and lapse stability conditions. Further measurements are being made to determine coefficients under stable conditions. It is expected that at least one paper based on this work will be prepared.

      3) During this period, design work on the direct-reading vertical wind indicator has been completed. A paper on the proposed design was presented at the 151st National Meeting of the American Meteorological Society in Chicago.

4) Utilization of the effluent from the ICPP stack as a tracer during the RALA process has permitted the determination of diffusion coefficients for a few cases. However, the intermittent and irregular nature of the emission during this process makes the use of this source for the determination of generalized diffusion coefficients rather doubtful.

5) Measurements of visual plume thickness by Weather Bureau personnel and survey readings by IDO Site Survey Branch personnel during an experiment conducted at the NRTS during March 1957, have permitted the computation of diffusion coefficients under relatively stable conditions. A classified report on this experiment has been submitted to the Director, Health and Safety Division, IDO, for inclusion in the complete report of the experiment.

6) Attempts to relate the large-scale features of the synoptic weather patterns, both at the surface and aloft, to the local winds have continued. As yet predictors that can be used with confidence for forecasting local winds have not been found. The study is increasing our knowledge of the factors contributing to our local wind directions. A summary of the forecasting problem and what is known of elements influencing the local winds is being prepared.

7) A program to relate measurements of net thermal radiation and lapse rate has been initiated.

8) At the request of the Engineering and Construction Division of IDO, a study has been started to determine the influence of a paved roadway on the sub-surface temperatures. Thermisters have been installed at six levels, corresponding to the levels of a similar array under natural ground surface, beneath a roadway that is to be surfaced.

b. Operations

1) RALA processing has been conducted at the ICPP approximately monthly since early December. The Weather Bureau has selected the times for these operations on the basis of wind direction and diffusion conditions.

2) The SPERT program was under meteorological control when transient periods shorter than those previously investigated, or power surges, were run. Our services were required for this program only on these occasions.

3) A program of diffusion forecasting and subsequent weather monitoring was carried out in connection with the ANP program. This program provided opportunities to test many of the research techniques for improving diffusion forecasts.

4) Daily wind, humidity, and weather forecasts were furnished the IDO Safety Engineers and the NRTS Fire Department for the control of construction activities. Daily forecasts and summaries of the weather of the preceding day were furnished several construction contractors. Temperature forecasts for the pouring of concrete were provided when required. Temperature forecasts were furnished the ICPP boiler room to assist in preparing for heat demands.

c. Observational Program

1) The recording of winds and temperatures at the usual levels above the surface was continued at the Central Facilities area location. On November 15 the recording of temperatures at 1-foot intervals from two feet below the surface of the ground to seven feet below the surface began. These are for data on the depth reached by frost for the IDO Engineering and Construction Division.

On June 4 the recording of temperatures at corresponding levels below the surface of a roadway (to be paved) began.

2) Wind data from four levels and temperature data from seven levels on the 200-foot tower at the IET area are received and recorded by telemetering equipment at the Weather Bureau Central Facilities area office.

3) Wind recording stations X and Z at the extremities of the proposed aircraft runway location were discontinued November 1. Station Y at the mid-point of the proposed runway has been continued as has the Birch Creek Station, also in the northwestern portion of the NRTS. A wind recording station STR-3 was installed in the vicinity of the NRF on Lincoln Boulevard. This is primarily for the purpose of checking inconsistencies that appear to exist between STR-2 data and that from Central Facilities. A wind recording station was installed on December 20 within the NRF area, adjacent to the spray ponds. This is to provide data for spray pond efficiency calculations requested by Westinghouse Electric Corporation. A wind recording station was installed close to the eastern boundary of the NRTS, about midway between the NRF and the ANP areas. This station serves the dual purpose of providing data (when manned by an observer with a radio) for use during controlled releases of effluent from the ICPP and also accumulating data for an area into which expansion will soon take place.

4) The off-site station (wind, temperature, relative humidity, and precipitation) at Monteview, Idaho has continued in operation. The telemetering stations installed at this location and near Camas, Idaho are not yet operational as far as wind data are concerned.

5) The Beckman and Whitley net radiometer was placed in service April 10, 1957.

6) Pibals and low-level soundings were taken throughout the period of IET operations and for other meteorologically controlled operations.

2. Highlights

a. Provision of detailed forecasts of diffusion and wind variability for IET and RALA operations. The requirements for forecasts of this type are quite stringent and not amenable to conventional meteorological techniques. New procedures are being devised to handle these problems.

b. Providing planning information and operational forecasts and data required for the successful completion of the March experiment. Sampling and safety requirements made the meteorological conditions of overriding importance.

Middletown

1. Resume

a. Research

1) Values of stability parameters and lateral diffusion coefficients have been determined from wind traces and summarized by wind direction, season of the year and temperature gradient divisions. There has been good correlation (.93) for most of the cases between coefficients determined from wind traces and smoke plumes. However, too few observations have been made at this time for the value to be considered statistically significant.

2) A large number (250) of photographs have been made to permit analysis of vertical diffusion coefficients. The technique suggested by Dr. Gifford, Weather Bureau Office, Oak Ridge, Tennessee, for analyses of these and all subsequent smoke pictures will be used.

3) Regular forecasts of vertical temperature gradient for a 24-hour period have been made as the initial step toward forecasting diffusion patterns for the area. The system is still partly subjective, but it appears from the verification that the procedures used are applicable to the problem. The verification for an inversion or no inversion forecast is 76% with a skill score of 49%. The verification scores for hourly forecasts of neutral conditions, and moderate and strong lapse or inversion conditions is 66% with a skill score of 55%.

4) One of the key meteorological factors relating to the type of inversion break that will occur has been isolated. It has been found that the inversion will break from the ground (i.e., fumigation conditions will occur) with light winds and little shear in the layer from the surface to 5000 feet. The inversion is more likely to break from the top down with strong winds and strong shear in the layer. Because of the natural variability of winds in this layer, it is anticipated that any forecast method devised will have to be constructed so as to give confidence limits that the inversion will not break from the ground up.

b. Observations

1) Routine tower observations were continued without major difficulties. The tower data are processed routinely monthly and seasonally.

2) The number of Beckman and Whitley Portable Wind Systems in use was reduced from four to three.

3) The data for the summer months of 1956 were combined and reproduced in report form during January. The data for the fall and winter seasons have been combined in report form and are now being reproduced.

4) Non-routine observations of neutral balloons, smoke tracers and temperature gradient under inversion conditions with the wiresonde system have been continued as availability of manpowder permitted.

2. Highlights

a. Successful inauguration of the program for determining simultaneous diffusion coefficients from tracers and from meteorological instruments.

b. Verification of the effects of wind shear on inversion dissipation.

Shippingport

1. Resume

a. Operations

1) The two meteorological stations were kept in continuous operation. The observational program has continued without major interruption or modification. Wind roses drawn from two years data are available for lapse and inversion conditions in addition to the regular wind rose. Frequency of inversions

by hours and average hourly wind speeds are also available for this period.

2) A daily forecast was furnished to three offices of Burns and Roe, Incorporated, agent constructor for the Duquesne Light Company and two offices of the Dravo Corporation, sub-contractor for the Westinghouse Corporation.

3) The daily surface observations have been sent to the Industrial Hygiene Branch of Westinghouse Corporation. This information was requested to correlate the records from air monitoring stations with local weather conditions.

4) The Transmission and Distribution Department of Duquesne Light Company has been supplied with traces on several occasions to aid in their study of severe local storms.

5) The PWR Physics Group of Westinghouse Corporation was furnished data on the average hourly wind speeds.

6) The PWR Plant Analysis Section of Westinghouse Corporation was furnished the various wind roses, frequency of inversions by hours, average hourly wind speed, comparative direction of frequencies and other information appearing in Section III of WAPD-SC-547 "Description of Shippingport Atomic Power Station Site and Surrounding Area with Radiation Background and Meteorological Data", one of the reports in the PWR Safeguard Document Series.

2. Highlights

The successful completion of the three-dimensional wind study furnished vertical motion data unattainable by other methods.

Washington

1. Resume

a. Research

1) A study of world-wide coastal and harbor meteorology was prepared in connection with plans for a nuclear powered merchant vessel. More than 60 harbors on all of the continents were analyzed.

2) An investigation of the form of the probability distribution of temperature gradient persistence was begun with Shippingport and Middletown data. It is hoped that the functional form of the distribution will permit a statistical prediction of "extreme values" (e.g., the probability of inversion duration $\geq$ n hours).

3) Initial equipment was ordered for instrumentation of the boundary layer. Particular emphasis is being placed on high speed anemometry and radiation measurements to investigate eddy energy distributions.

b. Meteorological Services and Investigation

1) Weather Bureau representatives have visited the following sites: Public Health Service's Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio; Knolls Atomic Power Laboratory; CANEL; National Reactor Testing Station; Nevada Test Site; Georgia Nuclear Laboratory; University of Rochester.

2) Three meetings of the Advisory Committee on Reactor Safeguards were attended in Washington. The requisite hazard summaries were reviewed and comments made on the meteorological aspects.

3) A paper describing the three-dimensional flow experiment at Shippingport was presented at the 151st National Meeting of the American Meteorological Society in Chicago.

4) We were visited by Dr. Miguel A. Quinones, Chief Engineer of the Puerto Rican Water Resources Authority to discuss the meteorological environment of a proposed power reactor in Puerto Rico. Some preliminary climatological data was obtained for this meeting. We were also visited by Messrs. Cohen and Cerre of the French Atomic Energy Authority.

5) At the invitation of Dr. G. Hoyt Whipple, a seminar was given at the University of Rochester on the evaluation of meteorological parameters for health physics measurements. At the invitation of Dr. S. Kinsman, a paper was presented at the Robert A. Taft Sanitary Engineering Center on "Meteorology and Nuclear Plant Operations." A brief statement on the effects of meteorology on incinerator emissions was prepared for the Committee on Incineration of Radioactive Wastes.

6) Informal advice and discussions were held with several groups including the Nuclear Products Division of ACF Industries, Walter Kidde, Inc., etc.

7) We participated in the Washington conference to review and discuss the Brookhaven National Laboratory Reactor Hazard Analysis.

2. Highlights

a. Successful completion of the three-dimensional wind study for Shippingport provided valuable data for evaluating stable atmospheric conditions and also served as a design test for experiments at other areas with similar terrain.

b. The study "Meteorological Analysis Applicable to Operation of a Nuclear Powered Vessel" provided an opportunity to assess, qualitatively, global similarities and differences in coastal diffusion conditions.

WEATHER BUREAU PROGRAM FOR THE SANITARY ENGINEERING SECTION, ENGINEERING DEVELOPMENT BRANCH, REACTOR DEVELOPMENT DIVISION, U. S. ATOMIC ENERGY COMMISSION

Mid-Year Review - July-December 1957

INTRODUCTION

The work described below is that specifically performed by the Weather Bureau for the Division of Reactor Development. Other research in the field of atmospheric transport and air pollution is not specifically described, but the overall Weather Bureau program is designed so that the various projects are complimentary and of mutual benefit to all sponsors.

Washington

Resume

A. Research

1. The analyses of two years of data from the PWR site at Shippingport, Pennsylvania, and preparation of a written summary were completed. This report is now being printed. Salient factors gained from this study were as follows:

   a. The surrounding topography causes a marked reduction in wind speeds and a subsequent reduction of atmospheric transport and dilution.

   b. Synoptic patterns reduce inversion frequency, particularly in winter, from that measured at many other locations.

   c. The Ohio River produces an air-water temperature differential much of the time; this affects the low-level temperature gradient, and hence influences low-level diffusion.

   d. Initial experiments to obtain diffusion coefficients suggest that wind speed and wind direction range and/or fluctuations are more reliable lateral diffusion parameters than temperature lapse rate, for the PWR site.

2. Temperature gradient data from Shippingport and Middletown and 12 years data from the Hanford Laboratories, have been analyzed with respect to probability distributions of temperature lapse rate categories, in an attempt to arrive at statistical predictions of extreme values. The method has been incorporated in the PWR meteorological report. With additional data from other sites, it is hoped that inter-site comparisons and more general classification of the controlling meteorological parameters can be made, especially the definition of climatic areas and synoptic regimes.

3. A study entitled, "A Meteorological Study of Potential Atmospheric Contamination from Multiple Nuclear Sites" is being prepared for possible presentation at the 1958 Geneva Conference.

4. Boundary Layer Project - The essential items of basic equipment necessary for running and recording boundary layer parameters (e.g., thermal and wind velocity gradients) have been procured. Installation at the Silver Hill Observatory of the equipment has begun and is expected to be completed by early spring. Preliminary experiments with a sonic anemometer-thermometer, on loan from the University of Wisconsin until our own arrives, have progressed well and initial field trials are being made. These initial field experiments are designed mainly to disclose certain gross features of turbulent flow in a suburban site to obtain information relative to the strict applicability of theoretical diffusion concepts to a real urban atmosphere.

B. Meteorological Services and Investigation

1. Weather Bureau representatives have visited the following sites: Public Health Service's Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio; PWR, Shippingport; CANEL, Middletown; Oak Ridge National Laboratory; Brookhaven National Laboratory and Argonne National Laboratory.

2. Four meetings of the Advisory Committee on Reactor Safeguards were attended in Washington and Chicago. The requisite hazard summaries were reviewed and comments made on the meteorological aspects of these reports.

3. A brief meteorological analysis of limited available data was made to evaluate the trajectory and air concentrations resulting from the Windscale incident.

4. A Weather Bureau Information Meeting on diffusion and turbulence was held in Washington, D. C., the week of November 4, 1957. The guest speaker was Dr. Frank Pasquill of Great Britain. Participants included Weather Bureau representatives from Oak Ridge, Idaho Falls, Las Vegas, CANEL, Public Health Service, Weather Bureau Silver Hill Observatory and representatives of the Reactor Development Division and the Biology and Medicine Division, Atomic Energy Commission. Reports describing various research projects at the respective sites were presented for informal discussions. The major items covered are included in the individual site reports.

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Idaho Falls

Resume

A. Research

1. Diffusion measurements, utilizing effluent from the RALA operation and the MTR stack as tracers and the sky-scanner scintillation unit as detectors, have been analyzed and are being written up.

2. Various diffusion parameters and the standard deviation of horizontal wind direction fluctuation and their relationship to vertical temperature lapse rate and wind speed are being analyzed, using data from IET tower and from the Central Facilities tower. These data have been put on punch cards; machine processing of hourly temperature lapse rates and wind roses under lapse and inversion conditions, and wind direction range data have been accomplished.

3. Correlation of net radiation data with inversion height, intensity and time of dissipation has been carried out. An intensive temperature sounding program for the balance of the winter is being conducted whenever the operational workload will permit.

4. The relationship between diffusion parameters obtained from wind records and diffusion parameters obtained from tracers is being examined.

5. Plans have been made to attempt some vertical diffusion measurements of particulate matter from the operation of HTRE II, Insert 2 by balloon-borne sticky paper. In addition, assistance has been given to General Electric and Health and Safety pertaining to their field sampling program in conjunction with this operation.

6. A wind profile study has been made from the ANP tower winds. Sutton's stability parameter, n, has been computed from these profiles for a variety of temperature lapse conditions.

7. An analysis of objective techniques for forecasting local winds has been prepared, in draft, for study.

8. Multiple-simultaneous pilot balloon ascents have been carried out to give an observation of the three-dimensional wind field.

9. Aerial photography of multiple smoke plumes has been temporarily abandoned in favor of ground photography. Smoke sources are being installed at key points on the NRTS, in preparation for the study of the wind shear line.

10. Final plans for a proposed bivane for measuring vertical wind direction fluctuations have been completed and actual construction is expected to begin shortly.

11. The Instrument Branch, Health and Safety, is constructing a radiosonde type device, of nominal cost, to measure temperatures in the first several thousand feet above the ground.

12. Soil temperatures at two different locations - in an open representative field and under a black-top highway - are being measured to a depth of seven feet. This study was requested by the Engineering and Construction Division to give some information on the relative depth of frost penetration under a black-top road compared to an open field.

B. Operations

1. Hazard reports for HTRE II, Insert 2 and the Gas Cooled Power Reactor were evaluated with respect to site location, stack location and design and/or necessary meteorological control.

2. Numerous meetings have been held with personnel from Health and Safety, Engineering and Construction, and various contractors concerning evaluation of hazard reports, operating plans and site locations.

3. Routine and specialized engineering and diffusion climatological studies have been given for planning and operational purposes.

4. Net thermal radiation data and low-level temperature sounding data are being collected.

5. A precipitation indicator has been constructed. This instrument will be useful for the evaluation of net radiometer records during periods of suspected precipitation occurrences.

6. The micronetwork of meteorological stations throughout the NRTS region has continued in operation, both for climatological summaries and operational work.

7. Forecasts of adverse weather have been furnished to the IDO, operating contractors, construction contractors, and local government officials as required; operational forecasts have also been furnished for the several RALA operations and the ANP operations. This included vectoring both the fixed and mobile Health and Safety monitoring units into position.

8. Estimation of fallout trajectories from the Las Vegas tests were made.

C. Highlights

1. Provision of detailed forecasts of diffusion and wind variability for RALA and HTRE II operations, requiring stringent restrictions, in addition to providing planning information and operational forecasts for various operations at NRTS.

2. The initiation of various research projects in an attempt to study the relationship of diffusion coefficients to temperature lapse rate, terrain and wind speed and direction fluctuations.

Middletown

Resume

A. Research

1. Smoke tracer investigations to determine diffusion parameters have been continued, utilizing the technique described by Dr. Frank Gifford of Oak Ridge. The smoke photographs that are not applicable to this type of analysis are utilized in studying the values of p (percent of axial concentration) that should be used under various conditions, according to the equation for determining cloud width, 2_{y_o}, from a continuous point source:

$$2_{y_o} = 2 \left(\ln \frac{100}{P}\right)^{1/2} C_y x^{(2-n)/2}$$

2. More experiments have been accomplished for correlation of diffusion coefficients from smoke plumes and wind direction trace width. There is good correlation at C_y values < 0.40, but this correlation decreases for higher C_y values. Plume widths were greater than would have been expected from the wind direction trace widths. This may be a function of averaging time and will be studied.

3. An objective method of forecasting vertical temperature gradients for a 24-hour period has been continued, examining data for additional parameters that may imporve the objective method.

B. Observations

1. Three portable Beckman and Whitley Anemometry systems have been in operation during the period. One of the locations is on the end of the pier in the middle of the Connecticut River, and is yielding interesting data on the lateral turbulence variations between over-land and over-water trajectories.

2. A net radiometer is in use, during regular working hours, and a locally manufactured version of the radiometer has been constructed and wired to a recorder to give continuous observations. It is hoped that this data will be useful in predicting the onset and intensity of temperature lapse rates.

3. Data collected from tower instruments are routinely processed by hand.

C. Outlook

1. Data collection will be continued through March 1958, when the operation of the weather station will be assumed by personnel of Pratt and Whitney Aircraft, at which time the resources of the Weather Bureau Staff will be devoted to the preparation of the final climatological and diffusion study report for CANEL.

SHIPPINGPORT

Resume

A. Research

1. The two year meteorological summary report has been completed and is now being reproduced.

2. A series of captive blimp ascents were made from a barge on the Ohio River adjacent to the reactor in December 1957. Wiresonde equipment was utilized to obtain vertical temperature gradients over the river. The results are included in the two-year report.

3. Values of Sutton's lateral diffusion coefficient, C_y, have been obtained utilizing high speed anemograph records.

B. Operations

1. The two meteorological stations continued normal operation without major interruption or modification. Thirty-two months of meteorological data are now available.

2. The Duquesne Light Company has assumed responsibility for station maintenance and collection of data from the weather station located on the ridge immediately south of the reactor plant area.

3. Daily forecasts and briefings are obtained from the U. S. Weather Bureau Office, Greater Pittsburgh Airport and this information made available to site personnel.

4. The Duquesne Light Company engineers attached to the PWR Power Plant Section of Westinghouse Electric Corporation requested and received two-year wind roses and inversion frequency data, in addition to all available climatological summaries.

C. Outlook

1. The observational program will continue for the remainder of the fiscal year or until such time as the Duquesne Light Company assumes the entire program.

2. Additional diffusion coefficients will be obtained through the utilization of high speed anemograph records. Simultaneous runs with Beckman and Whitley and Instruments Corporation anemometry systems are scheduled to obtain diffusion coefficients that may give an index of the response characteristics of the two anemometry systems.

3. Photography of controlled smoke plumes released at the river bank during inversion when the water temperature is higher than air temperature, is being considered. The results would be compared with experiments performed during the summer of 1956, when the water temperatures were lower than air temperature. The determining factor will be whether or not these smoke releases would interfere with river traffic.

D. Highlights

1. Completion of two year summary entitled, "A Meteorological Survey of the PWR Site at Shippingport, Pennsylvania".

2. Completion of wiresonde soundings on the Ohio River with the results indicating that the inexpensive land-based temperature gradient system utilized at the PWR gives a lapse rate that is representative of the lapse rate within the river valley at Shippingport.

Representative HOLIFIELD. Our next speaker is Dr. G. R. Hilst of Hanford—a continuation of meteorologic studies.

STATEMENT OF G. R. HILST,[11] MANAGER, ATMOSPHERIC PHYSICS, HANFORD ATOMIC PRODUCTS OPERATION, GENERAL ELECTRIC CO.

Mr. HILST. Mr. Chairman, members of the committee: My name is Glenn R. Hilst; I am employed by the General Electric Co. at the Hanford Atomic Products Operation in Richland, Wash., as manager of the Atmospheric Physics Operation.

My remarks are intended to describe the Hanford research and development program in the meteorological phases of atmospheric waste disposal, the results of these studies, and their pertinence to the problems of airborne wastes.

The avoidance of atmospheric or terrestrial contamination by industrial wastes which are released to the atmosphere requires a sound knowledge of the atmosphere's capacity to dilute and transport these waste materials. However, meteorological considerations constitute only one phase of the overall problem; equally important are the specification of the source position and strength, the position of the receptor, and its susceptibility to the waste material. The role of the atmosphere as the "middleman" in this problem is shown in figure 1 (p. 1585). Since the only possible control over potential pollution must be exercised at the source, the meteorological problem is to determine how much material may be released and still not produce concentration or exposures at the receptor which exceed its permissible level. This problem quite obviously requires the specification of the likelihood that material will be carried from the source to the receptor and, if it is, how much it will be diluted before it gets there.

ATMOSPHERIC TRANSPORT AND DIFFUSION STUDIES

The capacity of the atmosphere to dilute extraneously introduced materials and the manner in which it transports them are both highly variable. An actual record of the concentration of material measured at a fixed point downwind from a tall stack which was emitting material steadily is shown in figure 3 (p. 1590). The extreme variability

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Marital status: Married. Number of dependents: 3.
Education: Massachusetts Institute of Technology, S.B. Meteorology, 1948; Massachusetts Institute of Technology, S.M. Meteorology, 1949; University of Chicago, Ph. D. Meteorology, 1957.
Member: Basic research planning committee on turbulence and convection, University Committee on Atmospheric Research, 1958.
Special lecturer on meteorology: University of Washington, 1958.
Work history:
1941–46: Meteorologist, U.S. Army Air Corps.
1948–49: Research assistant, MIT.
1949–52: Research meteorologist, General Electric Co., Richland, Wash.
1952–54: Associate meteorologist, Argonna National Laboratory, Lemont, Ill.
1954 to present: Manager, Atmospheric Physics, Hanford Laboratories (various similar titles were used in earlier organization structures), General Electric Co., Richland, Wash.
Professional societies:
Professional member, American Meteorological Society.
Foreign member, Royal Meteorological Society, Great Britain.
Committee memberships:
Chairman, Committee on Air Pollution, American Meteorological Society.
Member, Meteorology Committee, Air Pollution Control Association.

of concentration at this point was due to both the variability of the wind direction, which caused the plume to "meander" about the observation point, and to the variability of the rate at which the material was diluted by the atmosphere.

Prediction of this seemingly erratic behavior of the concentration at a point is, for all practical purposes, impossible. However, there are two features of this record which are of primary concern: (1) The magnitude of the peak concentrations, and (2) the long-term average concentration. The peak concentrations are important in determining whether or not very short-period exposures to high concentrations are harmful, while the effects of long-period exposure are determined by the average concentration. These long- and short-term exposures are generally referred to as "chronic" and "acute" exposures, respectively, and their prediction is not such a hopeless task. For a given source and terrain, the chronic and acute exposures which should be expected also vary considerably from one meteorological condition to another, and it is this variability which we are studying most intensively in connection with industrial waste disposal problems.

ACUTE EXPOSURE STUDIES

A study of peak concentrations which are to be expected within 1½ miles of a 200-foot stack has been completed in Hanford. From these studies, it has been possible to specify the maximum ground-level concentrations which should be expected under a wide variety of meteorological conditions. In particular, knowledge of the wind speed and the atmospheric stability is sufficient to predict maximum short-period concentrations under terrain conditions encountered at Hanford.

This work permits prediction of the magnitude of short-term concentrations; it is, also, of importance to know where these concentrations are likely to be encountered. We have completed several experiments in which we measured the frequency with which "puffs" of high concentration came to the ground, and their position with respect to the source at first contact with the ground. Two cases are shown in figure 5 (p. 1594). During a period of light and variable winds, the puffs were dispersed widely. However, during a period of stronger and more steady winds, the area of first contact was much more restricted.

Puffs of high concentration were estimated to be on the ground within one-half mile of the source 60 percent of the time during this latter experiment.

These studies have been used to evolve a system for stack emission control whereby the maximum permissible emission rate is specified on the basis of maximum permissible short-term concentrations, the existing meteorological conditions, and the flow rate in the stack. These empirically derived results are, of course, strictly applicable only at Hanford.

They are also useful as guides at some other sites.

CHRONIC EXPOSURE STUDIES

While some excellent diffusion theories, applicable to long-term average concentrations, have been available for some time, there have

been serious questions as to their applicability to Hanford terrain and their validity when extended beyond a few hundred feet from the source. We have, therefore, undertaken comprehensive measurements of the long-term average concentration distributions over selected Hanford terrain. To do this, we have perfected a tracer system which permits quantitative determinations of airborne concentrations under precisely controlled tracer emission and sampling conditions. The tracer material used in these studies is a nontoxic nonradioactive fluorescent powder.

The most complete study to date is our investigation of diffusion in stably stratified atmospheres, a frequent nighttime condition when the diffusive capacity of the atmosphere is at a minimum.

From these studies, we have determined that high concentrations persist to large distances in stably stratified atmospheres, primarily because the vertical mixing of the gases with air is strongly curtailed. A plot of concentration versus distance from the source is shown in figure 6 (p. 1596) in order to illustrate the main findings in these studies. Axial concentrations are shown here for two cases (1) when the observer always stays in the middle of the plume (case A) and (2) when the observer is fixed with respect to the ground (case B). The third line (case C) is the concentration which would have been predicted from earlier diffusion theory. Note, first of all, that the earlier theory increasingly underestimates the true concentration as we go away from the source. However, note, also that the long-term average concentration is lower for the fixed than for the moving observer. This latter fact is due entirely to the meandering motions of the plume. We have found the average concentration is reduced to between one-half and one-eighth what it would have been if these meandering motions had been absent.

As a result of these experiments, considerably more reliable estimates of atmospheric dilution in stable atmospheres are now available. This work has, also, led to the formulation of more reliable meteorological parameters for predicting atmospheric diffusion during periods of stable temperature stratification.

Measurements of the distribution of tracer concentrations during typical daytime conditions, when the atmospheric diffusion rate is higher but the material is brought to the ground close to the stack, have been most informative. An observed pattern of concentration distribution at distances up to one-half mile from the source is shown in figure 7 (p. 1598). A large number of such observations is necessary to determine the variability of atmospheric diffusion under these conditions and the relationship to meteorological and terrain variables. We are now in the midst of an experimental program designed to provide just this information.

These studies have already provided reliable criteria for the design and operation of industrial facilities at Hanford. However, the multiplicity of combinations of terrain and meteorological conditions which may be encountered precludes the answering of these problems for all conceivable situations from presently available knowledge. We are continuing these studies in order to extend and improve these estimates. Progress in this field has been, and should continue to be, rapid.

DEPOSITION AND WIND EROSION STUDIES

In addition to the foregoing studies of atmospheric transport and diffusion, we are studying two important auxiliary problems. These are deposition of airborne contaminants and erosion of previously deposited materials. Neither of these problems can be answered from meteorological considerations alone, but the motions of the air near the ground are important and frequently decisive, in their solution. The importance of deposition and erosion is accented by recognition of the fact that limiting conditions on permissible levels of exposure are frequently set by the rate at which the waste material is taken up by plants, animals, and the ground. Also, if deposited material is not bound to the surface it may be taken up again by the atmosphere and transported to distant points long after its original emission.

We have recently completed plans for detailed studies of deposition, which will supplement theoretical studies and provide more reliable guides than are now available. Studies of wind erosion of particulate materials have already given excellent measures of the relative erodibility of various surfaces.

The results of one of these experiments are shown in figure 9 (p. 1602). The most striking results are, (1) relative to a natural surface, a rock cover provides desirable protection from erosion while a simple barrier such as a snow fence does not and (2) disturbance of Hanford's sandy soil by plowing greatly enhances the erodibility of the disturbed surface. These studies are being extended at the present time.

CONCLUSION

Useful solution of the meteorological problems associated with atmospheric waste disposal are being developed and improved constantly by research programs of the type described here. It is well to bear in mind, however, that these problems are exceedingly complicated and, in a very real sense, are not subject to exact solution. The only available methods for solving problems of this kind are statistical in nature, and the answers always involve a certain amount of uncertainty. Stated simply—and in paraphrase of a noted British scientist—the atmosphere itself knows only within certain limits what it will do with extraneously introduced materials. These areas of uncertainty must be clearly defined by the research programs and just as clearly recognized by those who apply the results of these programs.

That completes my testimony.

Representative HOLIFIELD. Thank you very much, Dr. Hilst.

Are there any questions from the committee members?

From the staff?

Thank you very much for your presentation, sir.

(Dr. Hilst's formal statement follows:)

METEOROLOGICAL STUDIES AT THE HANFORD WORKS

By Glenn R. Hilst, Hanford Laboratories, Hanford
Atomic Products Operation, General Electric Company

PURPOSE AND SCOPE OF THIS DOCUMENT

In connection with Public Hearings on Industrial Radioactive Waste Disposal before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, the following report is intended to delineate the meteorological phase of the problem of airborne wastes. The meteorologic research and development program currently active at Hanford is described, and the results of this program are presented along with a description of their pertinence to the successful solution of the problems of atmospheric waste disposal and to the assurance of continued safe operation of nuclear energy facilities.

Introduction

When industrial waste gases or particulate materials are discharged to the atmosphere, it is with expectation that they will be diluted, dispersed, and eventually deposited in harmless concentrations. If these materials are released in concentrations which are already harmless, there is, of course, no immediate concern. There may be a long-term concern due to the steady buildup of the contaminant material on, say, vegetation due to continued exposure to low concentrations and consequent deposition. However, if the initial concentrations are above tolerance levels, or if a combination of sources operates simultaneously and thereby combines to produce concentrations or exposures which are potentially harmful, there is immediate as well as long-term concern and consideration must be given

to the fate of the materials after they leave their source or point of emission.

Any rational attack upon the problem of atmospheric and terrestrial pollution must consider the three major components of the problem. These are:

1. The position of the source of the pollutant and the rate at which the pollutant is released.
2. The position of the receptor and the susceptibility of the receptor to the pollutant.
3. The atmospheric motions which transport and dilute the pollutant material as it travels from the source to the receptor.

These three phases of the problem are illustrated in Figure 1. Given the positions of the receptors, whether they be humans, plants, animals, the ground, or water, and their appropriate tolerance levels for the pollutant, the practical problem of industrial waste control is reduced to the specification of the amount of material which may be safely released at the source or sources. This problem quite obviously requires knowledge regarding the likelihood that the pollutant will be carried to the receptor and, if it is, how much it will be diluted before it gets there. Much of our atmospheric physics research and development work is directed to this basic problem of airborne transport and dilution of industrial wastes.

Two important auxiliary problems arise once the material has arrived at the receptor:

1. What is the rate of uptake or deposition of the material?
2. Is the material then fixed at the receptor site or is it sub-

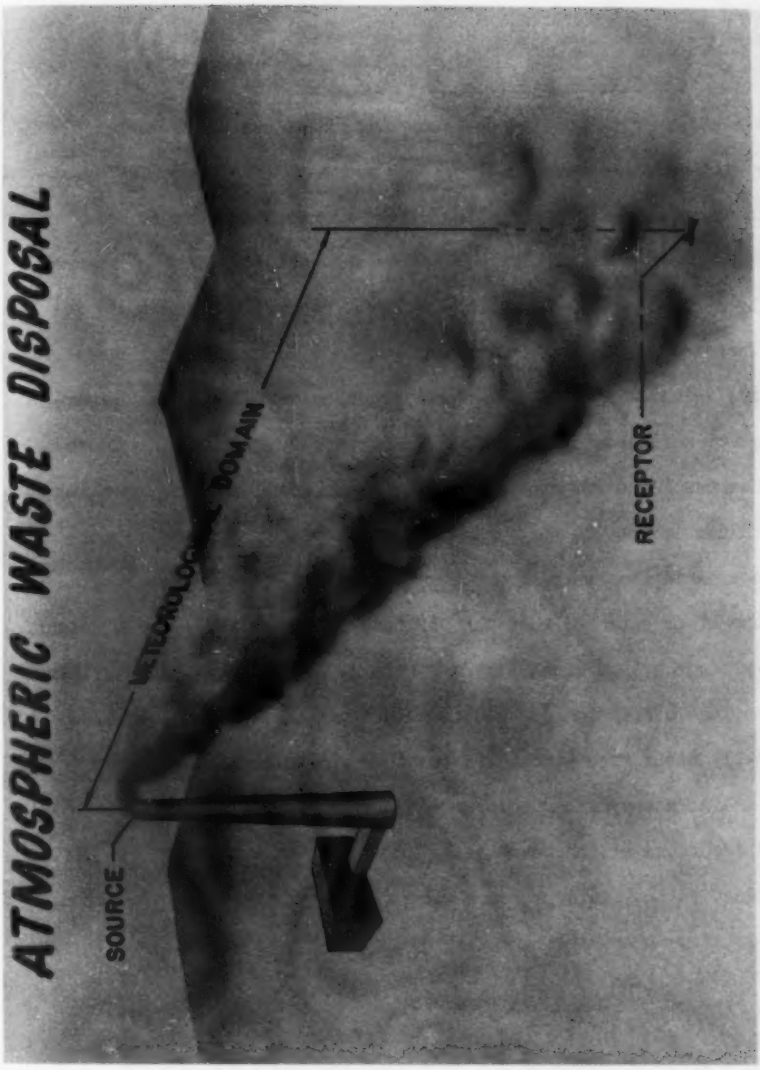

FIGURE 1

ject to subsequent reentrainment into the atmosphere? Neither of the latter problems may be answered from meteorological considerations alone. However, the atmospheric motions near the ground frequently play a decisive role in the processes of deposition and reentrainment of airborne wastes. We are studying these processes at Hanford, also.

Atmospheric Transport and Diffusion Studies

The atmosphere's capacity to transport and dilute gases varies strongly with variable meteorological conditions. The mechanics of atmospheric dispersion are not simple, but we may identify the extreme cases of large and small dilution rates on the basis of the temperature or density stratification of the atmosphere. When the temperature decreases faster than about 5° Fahrenheit per 1000 feet of height above the ground, vertical motions of the air are accelerated and the dispersion of waste materials is generally quite rapid. Typically, a smoke plume undergoes large vertical excursions under these conditions, a feature which has led to the descriptive term, "looping," for the dispersion phenomena in this case of unstably stratified atmospheres.

At the other extreme, when the air temperature increases with height, vertical motions of the atmosphere are strongly suppressed. Under these conditions, the dispersion is reduced to a minimum. Material emitted into a stably stratified atmosphere tends to remain at the height of emission and move away from the source in a thin ribbon or fan shape, hence the descriptive term "fanning."

In addition to this dependence upon the temperature stratification, atmospheric dispersion rates are also quite sensitive to wind speed.

However, the extremes of atmospheric dispersion are almost always associated with light to moderate winds; strong winds are generally associated with concentrations which are intermediate between the extremes.

The range of concentrations included by the extremes of atmospheric dispersion is quite large - at least 10,000-fold. Figure 2 shows this range as observed at Hanford and, as can be seen from this figure, for a given source strength and wind speed the average concentration at a point is about 10,000 times higher in very stable atmospheres (or in the presence of a strong temperature inversion) than in very unstable atmospheres. Between these extremes lie a whole gamut of intermediate conditions which are more or less favorable for atmospheric waste disposal.

Just how favorable these conditions are can be determined directly from Figure 2. For example, if the tolerable concentration for a certain material is 10^{-6} (one millionth) of a unit per cubic meter, the emission rate is one unit per second, and the wind speed is one meter/second, intolerable concentrations will occur to well beyond fifteen miles when there is a temperature inversion, but will not occur beyond about three miles in an unstably stratified atmosphere. Increasing the emission rate increases the distance required before concentrations are reduced to tolerable levels in all cases.

These data also help to define the scope of the atmospheric research program necessary to cope adequately with this problem of air pollution. If the source strengths and the tolerable concentrations are known, we can define roughly the range of distance over which precise knowledge of atmospheric dispersion is required. In some cases, such as low emission rates and rapid atmospheric dispersion, there is no immediate pollution

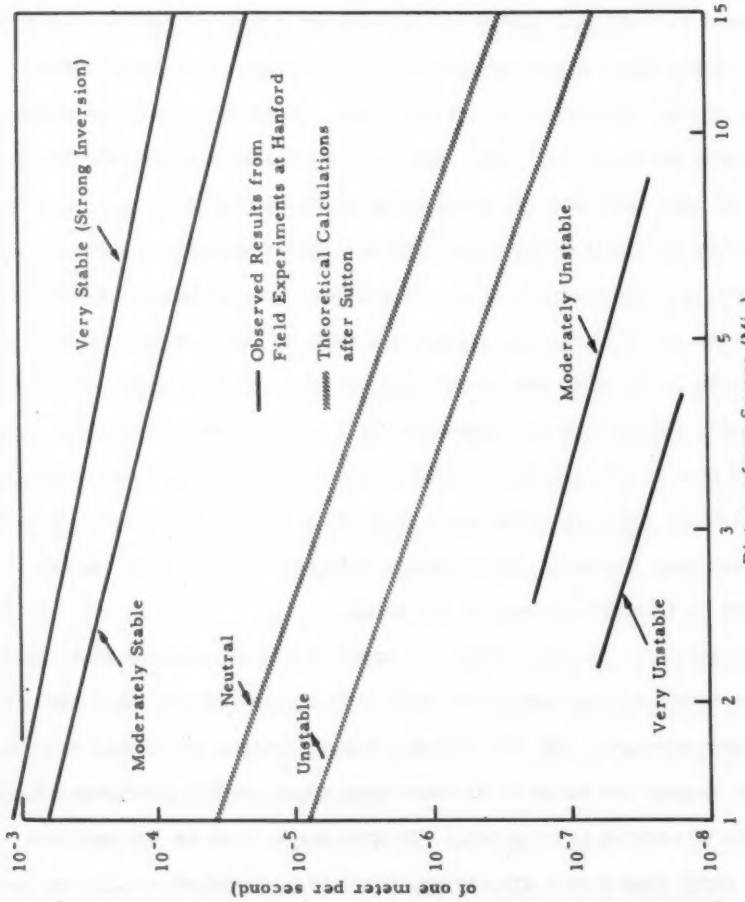

FIGURE 2

Stack Gas Concentrations Under Different Atmospheric Conditions

problem beyond a few hundred feet from the source. In the case of very large emission rates, and particularly when the atmosphere is stably stratified, the range of distance in which concentrations are above acceptable levels may be ten, twenty, even fifty or one hundred miles. In these latter extreme cases, we must extend our atmospheric researches to large distances if we are to cope with this problem.

It is well to bear in mind that, while the dispersive capacity of the atmosphere is frequently large, it is never unlimited, even under the most favorable circumstances. Whether or not atmospheric dispersion is adequate to prevent an atmospheric pollution problem can be determined only when the source is known and the tolerance levels at the receptor have been defined.

A typical record of the concentrations of stack gases measured by an observer who is stationed at a fixed point downwind from a continuous industrial source is shown in Figure 3. Note that these concentrations are far from constant, even during short periods of time, and a receptor at this point is subjected to short periods of relatively high concentrations and longer periods of relatively low concentrations. This short-period variability of concentration is due to both the variability of wind direction, which causes the plume to "meander" about the average wind direction, and the variability of the dilution of the material from one part of the plume to another.

Prediction of this seemingly erratic behavior of the concentration at a point is, for all practical purposes, impossible. However, there

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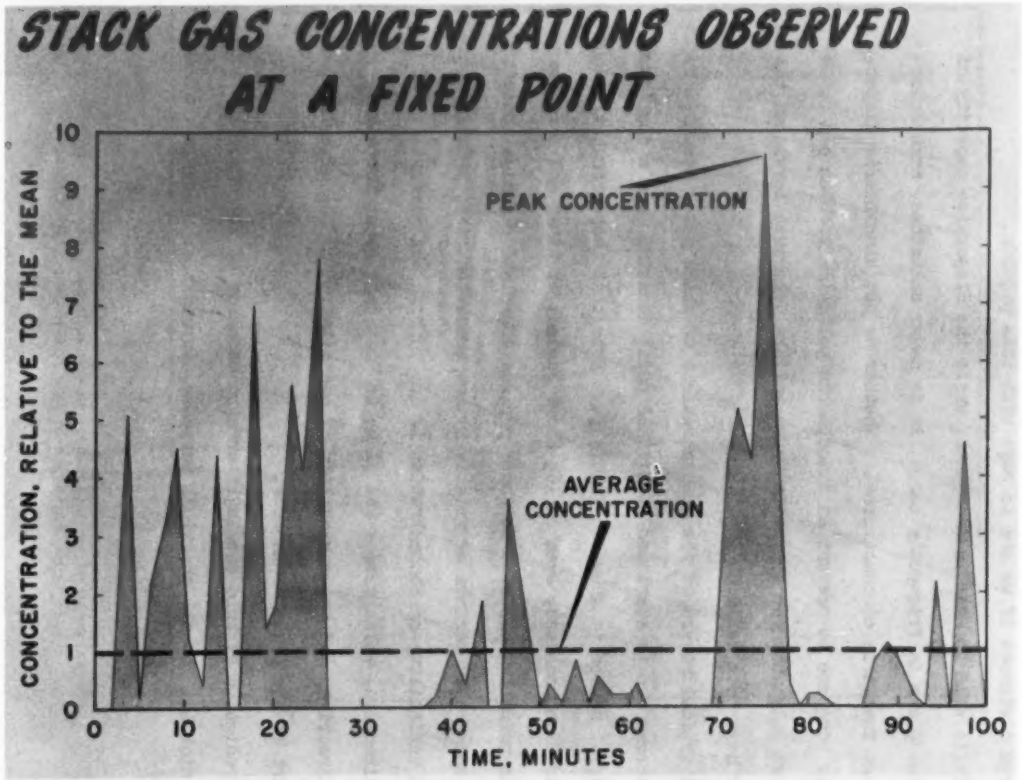
STACK GAS CONCENTRATIONS OBSERVED
AT A FIXED POINT
CONCENTRATION, RELATIVE TO THE MEAN
TIME, MINUTES
PEAK CONCENTRATION
AVERAGE
CONCENTRATION
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
100

FIGURE 3

are two features of this record which are of primary concern, 1) the magnitude of the peak concentrations and 2) the long-term average concentration. The peak concentrations are important in determining whether or not very short-period exposures to high concentrations are harmful, while the effects of long-period exposure are determined by the average concentration. These long- and short-term exposures are generally referred to as "chronic" and "acute" exposures, respectively, and their prediction is not such a hopeless task.

Acute Exposure Studies

An intensive study of peak concentrations which are to be expected within one and one-half miles of a 200-foot stack has been completed at Hanford (Fuquay 1958). From these studies, it has been possible to specify the maximum ground-level concentrations which should be expected under a wide variety of meteorological conditions. In particular, knowledge of the wind speed and the atmospheric stability is sufficient to predict maximum short-period concentrations under terrain conditions encountered at Hanford. This relationship among the quantities, wind speed, atmospheric stability, and the short-term maximum concentrations, is shown in Figure 4. Each point on this chart defines a "K" value which, when multiplied by the emission rate at the source, yields the maximum acute exposure concentrations.

The work just described permits prediction of the magnitude of concentrations; it is also of importance to know where these concentrations are likely to be encountered. We have completed several experiments in which we measured the frequency with which "puffs" of high concentration

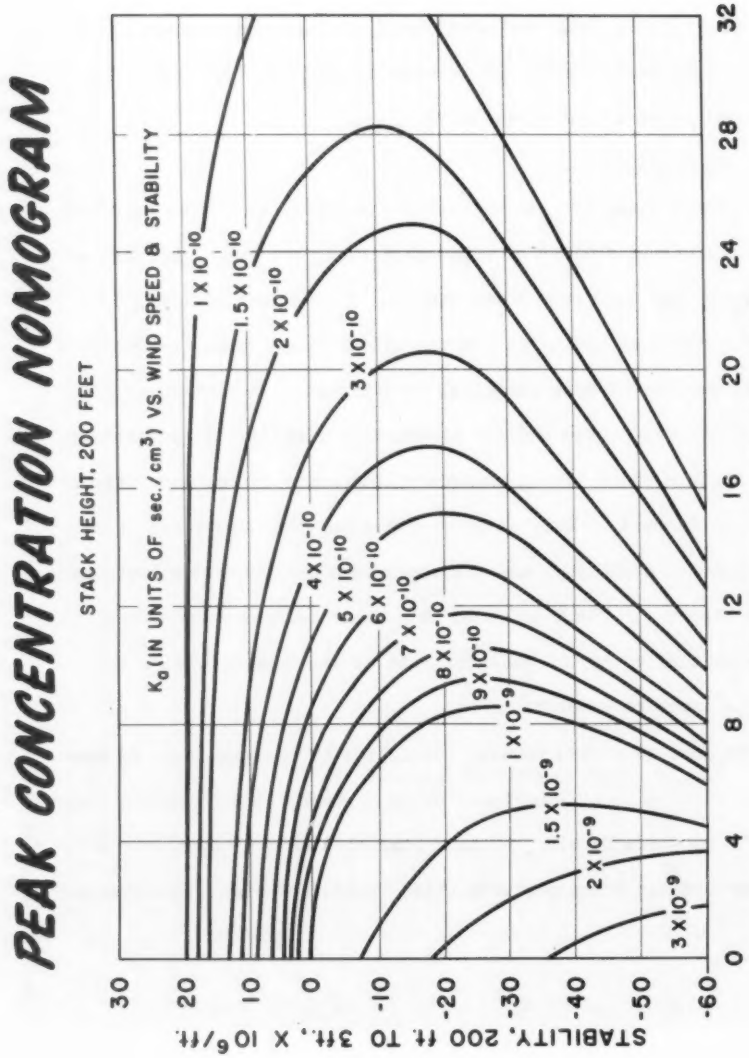
PEAK CONCENTRATION NOMOGRAM
STACK HEIGHT, 200 FEET
K_a (IN UNITS OF sec./cm^3) VS. WIND SPEED & STABILITY
1 X 10^{-10}
1.5 X 10^{-10}
2 X 10^{-10}
3 X 10^{-10}
4 X 10^{-10}
5 X 10^{-10}
6 X 10^{-10}
7 X 10^{-10}
8 X 10^{-10}
9 X 10^{-10}
1 X 10^{-9}
1.5 X 10^{-9}
2 X 10^{-9}
3 X 10^{-9}
STABILITY, 200 ft TO 3ft., X 10^6/ft
30
20
10
0
-10
-20
-30
-40
-50
-60
0
4
8
12
16
20
24
28
32
WIND SPEED AT 200 FEET, MPH

FIGURE 4

came to the ground, and their position with respect to the source at first contact with the ground (Barad and Shorr 1954). Two cases are shown in Figure 5. During a period of light and variable winds, the puffs were dispersed widely. However, during a period of stronger and more steady winds, the area of first contact was much more restricted. Puffs of high concentration were estimated to be on the ground within one-half mile of the source 60 percent of the time during this latter experiment.

These studies have been used to evolve a system for stack emission control whereby the maximum permissible emission rate is specified on the basis of maximum permissible short-term concentrations, the existing meteorological conditions, and the flow rate in the stack (Fuquay 1958). These empirically derived results are, of course, strictly applicable only at Hanford, but they provide valuable guides for other sites as well.

Chronic Exposure Studies

Studies of the long-term average concentrations, or chronic exposures, encountered at various distances and directions from Hanford sources have also been actively pursued in recent years. While some excellent diffusion theories have been available for some time, there have been serious questions as to their applicability to Hanford terrain and their validity when extended beyond a few hundred feet from the source. We have, therefore, undertaken comprehensive measurements of the actual transport and diffusion of materials over the Hanford area. To do this, we have perfected a tracer system which permits quantitative determinations of airborne concentrations under precisely controlled

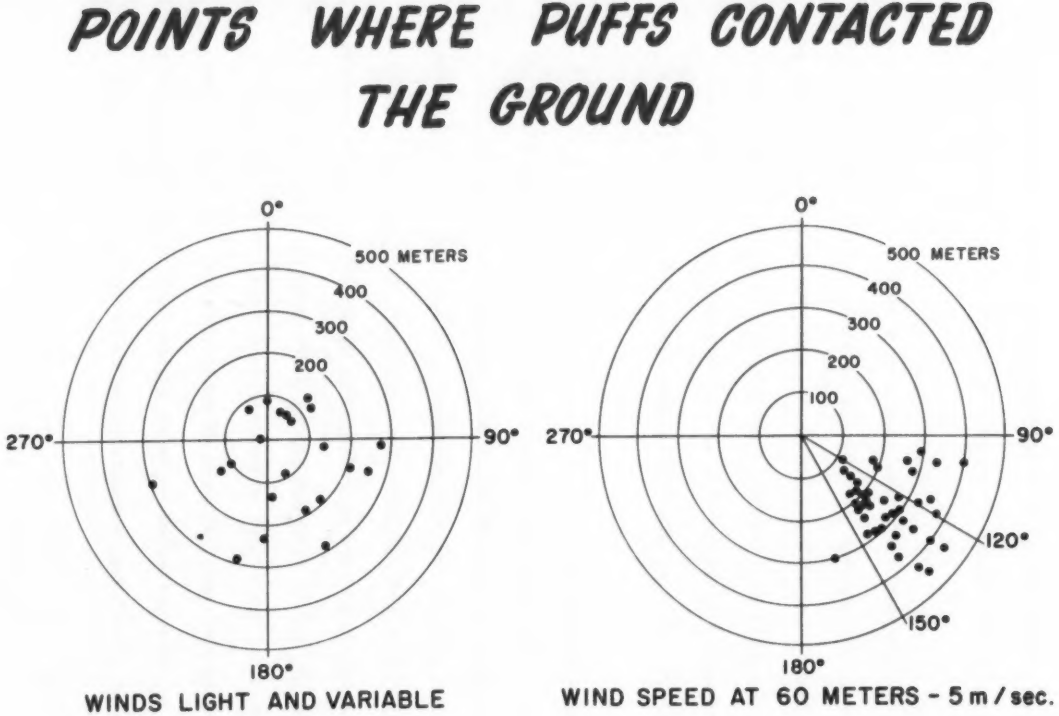
POINTS WHERE PUFFS CONTACTED THE GROUND
0°
500 METERS
400
300
200
270°
90°
180°
WINDS LIGHT AND VARIABLE
0°
500 METERS
400
300
200
100
270°
90°
120°
150°
180°
WIND SPEED AT 60 METERS - 5 m / sec.

FIGURE 5

tracer emission and sampling conditions. The tracer material used in these studies is a nontoxic, nonradioactive fluorescent powder.

The Hanford program of atmospheric diffusion measurements has already produced significant results regarding the variability of the atmosphere's capacity to dilute and disperse airborne wastes. The most complete study to date is our investigation of diffusion in stably stratified atmosphere, the typical nighttime conditions when the diffusive capacity of the atmosphere is at a minimum (Hilst 1957). We have been particularly interested in getting estimates of concentrations at larger distances from the source, since it is known that stack gases can be transported over long distances with little dilution under these conditions. From these studies, we have determined that high concentrations do persist to large distances, primarily because the vertical mixing of the gases with air is strongly curtailed. A plot of concentration versus distance from the source is shown in Figure 6 in order to illustrate the main findings in these studies. Axial concentrations are shown here for two cases, 1) when the observer always stays in the middle of the plume (Case A) and 2) when the observer is fixed with respect to the ground (Case B). The third line (Case C) is the concentration which would have been predicted from earlier diffusion theory. Note, first of all, that the earlier theory increasingly underestimates the true concentration as we go away from the source. However, note, also, that the long-term average concentration is lower for the fixed than for the moving observer. This latter fact is due entirely to the meandering motions of the plume. We have found the average concentration is reduced to between one-half and one-eighth what it would have been if these meandering motions had been absent.

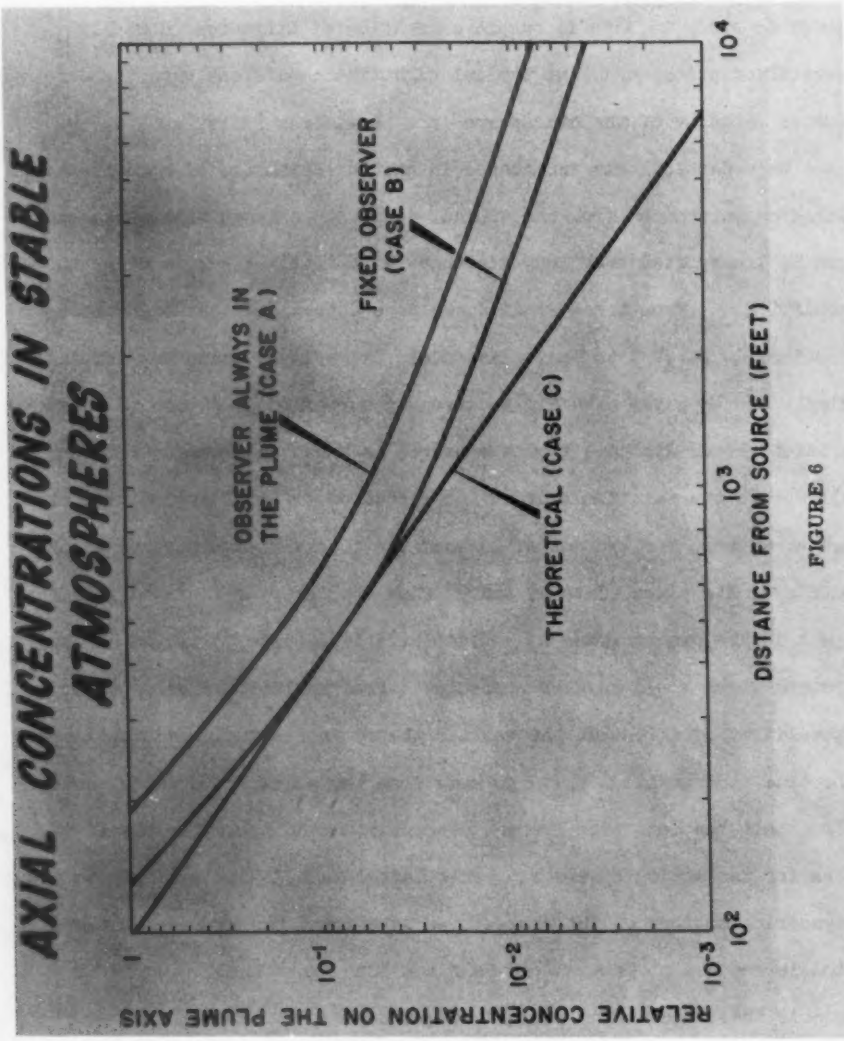
AXIAL CONCENTRATIONS IN STABLE ATMOSPHERES
OBSERVER ALWAYS IN THE PLUME (CASE A)
FIXED OBSERVER (CASE B)
THEORETICAL (CASE C)
RELATIVE CONCENTRATION ON THE PLUME AXIS
1
10^{-1}
10^{-2}
10^{-3}
10^{2}
10^{3}
10^{4}
DISTANCE FROM SOURCE (FEET)

FIGURE 6

As a result of these experiments, considerably more reliable estimates of atmospheric dilution in stable atmospheres are now available. This work has also led to the formulation of more reliable meteorological parameters for predicting atmospheric diffusion during periods of stable temperature stratification.

Measurements of the distribution of tracer concentrations during typical daytime conditions, when the atmospheric diffusion rate is higher but the material is brought to the ground close to the stack, have also been most informative. An observed pattern of concentration distribution at distances up to one-half mile from the source is shown in Figure 7. A large number of such observations is necessary to determine the variability of atmospheric diffusion under these conditions and the relationship to meteorological and terrain variables. We are now in the midst of an experimental program designed to provide just this information.

Existing measurements of the distribution of concentration during typical daytime conditions have pointed up the importance of variable wind direction, also. In Figure 8, we have shown a time plot of the position of a plume as it crosses a line four miles from the source. Notice how the plume moves back and forth over a distance of about three miles. The average distributions of concentration in the plume and over the fixed line of samplers are shown here, and again demonstrate the effects of wind direction variability.

These studies of atmospheric transport and dilution of industrial wastes have provided very valuable estimates of long- and short-term exposures which should be expected under a variety of meteorological conditions. As such, they have already provided reliable criteria for the

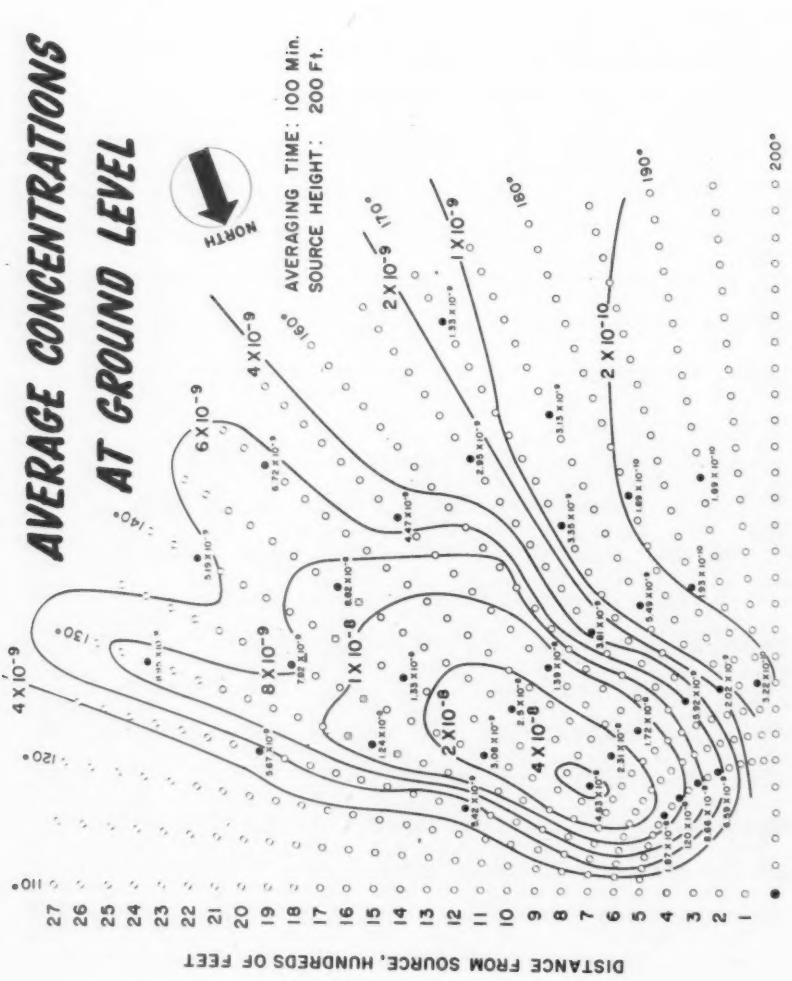
AVERAGE CONCENTRATIONS
AT GROUND LEVEL
AVERAGING TIME: 100 Min.
SOURCE HEIGHT: 200 Ft.
NORTH
DISTANCE FROM SOURCE, HUNDREDS OF FEET
4 X 10⁻⁹
8 X 10⁻⁹
6 X 10⁻⁹
4 X 10⁻⁹
2 X 10⁻⁹
1 X 10⁻⁹
1 X 10⁻⁸
2 X 10⁻⁸
4 X 10⁻⁸
2 X 10⁻¹⁰
110°
120°
130°
140°
150°
160°
170°
180°
190°
200°

FIGURE 7

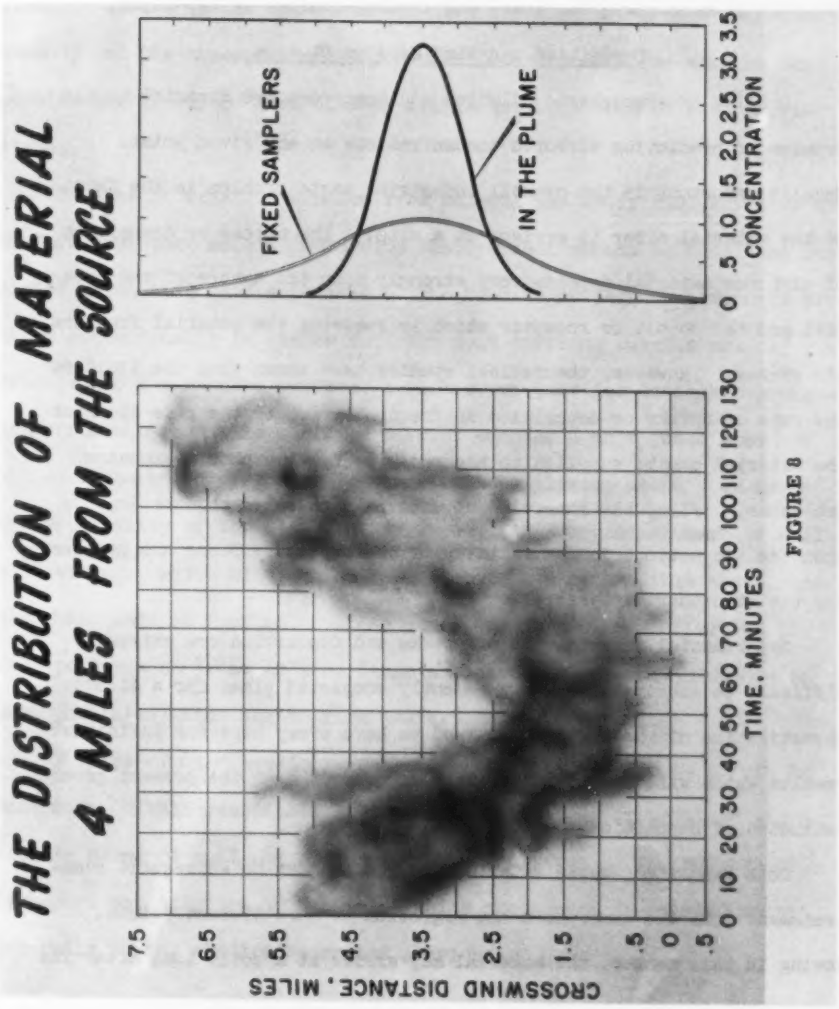
THE DISTRIBUTION OF MATERIAL
4 MILES FROM THE SOURCE
FIXED SAMPLERS
IN THE PLUME
0 .5 1.0 1.5 2.0 2.5 3.0 3.5
CONCENTRATION
CROSSWIND DISTANCE, MILES
7.5
6.5
5.5
4.5
3.5
2.5
1.5
.5
0
.5
0 10 20 30 40 50 60 70 80 90 100 110 120 130
TIME, MINUTES

FIGURE 8

design and operation of industrial facilities at Hanford. However, the multiplicity of combinations of terrain and meteorological conditions which may be encountered precludes the answering of these problems for all conceivable situations from presently available knowledge. We are continuing these studies in order to extend and improve these estimates. Progress in this field has been, and should continue to be, rapid.

Deposition and Wind Erosion Studies

Studies of atmospheric dilution and transport are directed to the problem of predicting airborne concentrations at any given point. Equally important in the overall industrial waste problem is the fate of the material after it arrives at a site. The uptake or deposition of airborne material depends very strongly upon the nature of the material and the object or receptor which is removing the material from the air stream. However, theoretical studies have shown that the limit on the rate of uptake or deposition is frequently set by the rate at which the material can be supplied to the receptor by atmospheric exchange processes. Also, the impaction of materials on solid objects depends upon the air motions in the vicinity of the object. These are problems for the atmospheric physicist.

Experimental measurements of uptake and deposition are extremely difficult to acquire. We have recently completed plans for a direct investigation of these phenomena, and we have every hope for definitive results which will permit a distinct improvement over the present gross estimates of deposition.

Once deposited, waste materials may be subject to subsequent reentrainment into the atmosphere and migration to more distant points. Moving in this manner, the material may arrive at a point long after its

original emission from an industrial plant. Particulate materials are particularly susceptible to this process since they may be deposited on the ground or vegetation but are not necessarily bound there. Erosive winds can then remove these particles, just as they remove natural dust particles. The susceptibility of particles to wind erosion depends very strongly upon both the nature of the soil (if they are eroded from the ground) and the atmospheric motions near the ground. Our work on this problem has therefore been closely allied with the work of soil physicists.

Studies of relative erosion from natural and artificial surfaces at Hanford have been made to determine their effectiveness in retaining particles which have been deposited. The results of these experiments are shown schematically in Figure 9. The most striking results are, 1) relative to the natural surface, a rock cover provides desirable protection from erosion while a simple barrier such as a snow fence does not and 2) disturbance of Hanford's sandy soil by plowing greatly enhances the erodibility of the disturbed surface. An independent test of soil conditioners, which bind the soil surface into a nonerodible crust, has also been made at Hanford. These conditioners are very effective if care is taken to treat an area large enough to prevent abrasion due to sand particles which arrive from nearby, untreated areas.

Studies of wind erosion are continuing at Hanford in an effort to determine, within reasonable limits, the probability of particle migration in terms of soil and meteorological conditions. The problem of transport and dilution of particles which are eroded is related quite naturally to the studies described previously.

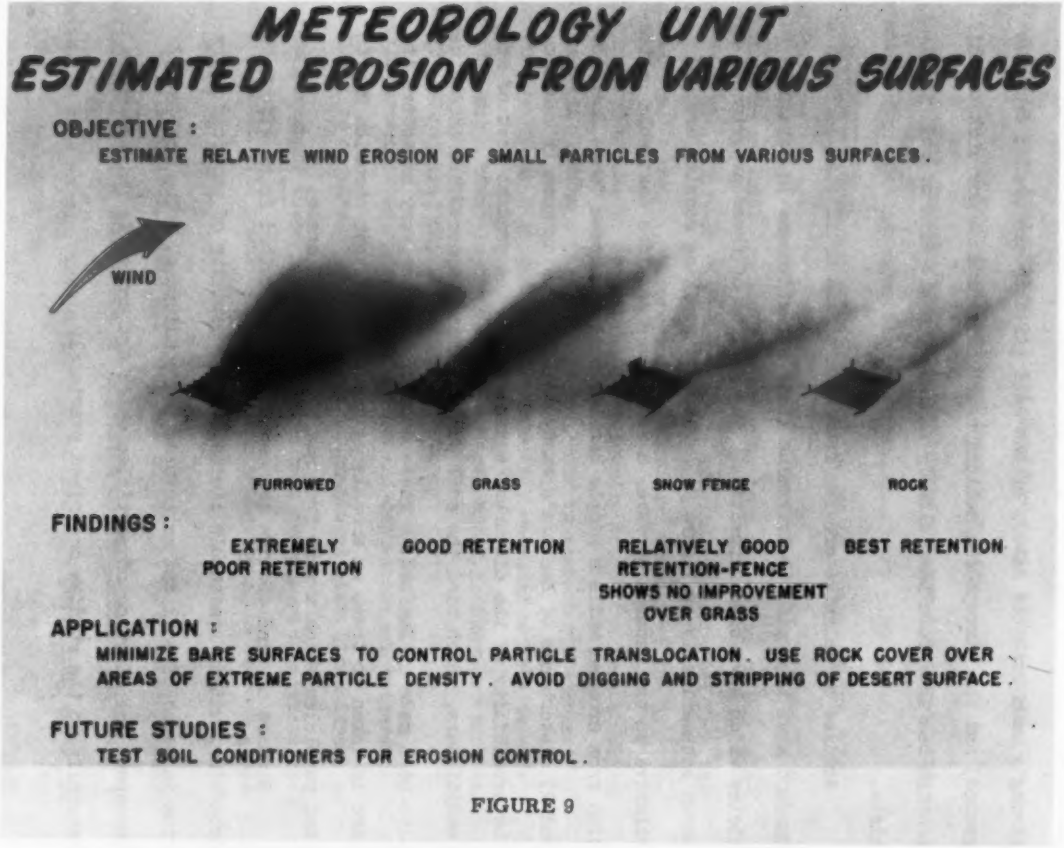
METEOROLOGY UNIT
ESTIMATED EROSION FROM VARIOUS SURFACES
OBJECTIVE :
ESTIMATE RELATIVE WIND EROSION OF SMALL PARTICLES FROM VARIOUS SURFACES.
WIND
FURROWED
GRASS
SNOW FENCE
ROCK
FINDINGS :
EXTREMELY POOR RETENTION
GOOD RETENTION
RELATIVELY GOOD RETENTION-FENCE SHOWS NO IMPROVEMENT OVER GRASS
BEST RETENTION
APPLICATION :
MINIMIZE BARE SURFACES TO CONTROL PARTICLE TRANSLOCATION. USE ROCK COVER OVER AREAS OF EXTREME PARTICLE DENSITY. AVOID DIGGING AND STRIPPING OF DESERT SURFACE.
FUTURE STUDIES :
TEST SOIL CONDITIONERS FOR EROSION CONTROL.

FIGURE 9

Conclusion

The object of this meteorological research and development program is to provide estimates of expected airborne concentrations, deposition, and translocation of industrial wastes. These estimates must be sufficiently precise so that the design of plants and, if necessary, their control can be done with minimum uncertainty due to meteorological factors. Our primary purpose is to provide the knowledge necessary to assure safe operation of industrial facilities insofar as atmospheric disposal of wastes is concerned. Useful solutions of the meteorological problems associated with atmospheric waste disposal are being developed and improved constantly by research programs of the type described here. It is well to bear in mind, however, that these problems are exceedingly complicated and, in a very real sense, are not subject to exact solution. Turbulent diffusion in the atmosphere is accomplished by random motions of the atmosphere. The only available methods for solving problems of this kind are statistical in nature, and the answers always involve a degree of uncertainty. Stated simply - and in paraphrase of a noted British scientist - the atmosphere itself knows only within certain limits what it will do with extraneously introduced materials. These areas of uncertainty must be clearly defined by the research programs and just as clearly recognized by those who apply the results of these programs.

References

Barad, M. L. and B. Shorr, "Field Studies of the Diffusion of Aerosols," American Industrial Hygiene Association Quarterly, 15:2, June 1954.

Fuquay, J. J., 1958, "Meteorological Factors in the Appraisal and

Control of Acute Exposures to Stack Effluents." (Paper prepared for the Second International Conference on Peaceful Uses of Atomic Energy.)

Hilst, G. R., "The Dispersion of Stack Gases in Stable Atmospheres," Journal of the Air Pollution Control Association, 7:3, November 1957.

Representative HOLIFIELD. The committee has several additional papers on meteorological aspects of radioactive waste disposal and without objection I will place them in the record at this point.

(The statements referred to follow:)

A METEOROLOGICAL STUDY OF POTENTIAL ATMOSPHERIC CONTAMINATION FROM MULTIPLE NUCLEAR SITES

By D. H. Pack and C. R. Hosler *

At the present time, except for a few test areas located at relatively isolated sites, nuclear reactors or fuel processing plants are not so numerous that spacing of the individual plants is of special concern. However with the continued rapid growth of the application of nuclear power and the construction of many reactors and their necessary fuel processing facilities, eventually the radioactivity released from these sources may simultaneously affect a given area. Such cumulative effects will be most pronounced during stagnant weather regimes, characterized by light winds and limited vertical diffusion, that persist for several days over an area.

In order to examine, in a realistic manner, the effects of a stagnant meteorological pattern upon atmospheric dilution over a densely populated area, a slow moving weather regime that occurred over the eastern United States during October 11-16, 1956 was selected. The triangular area from Washington, D. C. to Hartford, Connecticut to Albany, New York and thence back to Washington, D. C. was chosen for study. The high population density and large degree of industralization of this region make the close spacing of nuclear reactors a logical possibility. This area has a population of about 40,000,000. In 1956 there were about 1.2×10^4 megawatts of electrical power generated in this region, and in 1980 it has been estimated that this area will utilize 3.6×10^4 megawatts of electrical energy.(1)

During the period chosen for study, a slow moving anticyclone entered the region from the west and on October 11th was centered over the Great Lakes. Figure 1 shows the surface isobars delineating the anticyclone and its very slow eastward progress. Surface winds were very light during the passage of the system and only slightly stronger aloft, in the first kilometer above the surface. No precipitation occurred in the region during the stagnation period.

A study of the radiosonde records throughout the area indicated an intensifying subsidence inversion accompanying the anticyclone. There was a marked diurnal change in vertical thermal stability. Each night an inversion formed at the ground and extended upwards to the subsidence inversion; each day this low-level inversion was destroyed by solar heating, and a lapse rate near or slightly greater than adiabatic prevailed from the surface to the base of the subsidence inversion.

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The variation of the depth of this layer was controlled by the height and intensity of the subsiding layer aloft and the amount of solar radiation received at the surface. This depth can be estimated from meteorological data by plotting the daily maximum surface temperature on a temperature-height diagram, and assuming that the decrease of temperature with height is at the dry adiabatic lapse rate. The intersection of this assumed lapse rate with the actual upper air sounding defines a layer through which material can be readily mixed. Figure 2 is a schematic diagram of this technique. The point of intersection between the assumed lapse rate and the actual sounding is designated as the "mixing height" and the layer from the ground to this level as the "mixed layer". The dashed lines on Figure 1 show the depth of the mixed layer beneath the anticyclone. The increased dilution brought about by this mixing was indicated by improved visibilities during daylight hours compared to lower visibilities at night.

Stagnant weather situations of this type, although not rare, occur infrequently; the probability of their occurrence has been studied in detail.[2] In the Middle Atlantic States a pattern of this type, persisting for four or more days, can be expected to occur once or twice a year. Similar stagnant regimes are relatively common over other continental land masses as well as in North America.

The weather pattern previously described results in a minimum ventilation rate in the lower layers of the atmosphere. The light surface winds transport material slowly and the subsidence inversion acts as an upper "lid", preventing extensive vertical dispersion of material. In order to examine the quantitative effects of multiple sources of effluents during such a weather pattern, the following dilution model was postulated: (a) the effluent is carried at the speed and direction of the surface winds (the effect of vertical wind shear is neglected since an analysis of the winds at levels of 150 and 300 meters above the surface indicated that the error due to neglect of shear was small compared to other uncertainties); (b) the lateral spreading of the volume occupied by the effluent was approximately 11 degrees per six hours[3], and this horizontal spread was redetermined for each successive positioning of the effluent volume; (c) the vertical spreading of the effluent was limited to the mixing layer; and (d) the effluent was uniformly distributed within the volume defined by the first three criteria. One exception was made. We assumed that the plume of material generated during the latest six-hour period maintained a separate and distinct geometry and was <u>not</u> uniformly distributed throughout the volume occupied by previous releases. The "plume" concentration during the latest six-hour traverse was assumed uniform in the vertical and lateral directions, but the concentration varied in the downwind direction. Each unit of downwind volume contained the amount of effluent added to it as the air passed the source of the effluent.

Eight source locations, shown in Figures 3-8, were chosen on the basis of availability of complete meteorological data and on the suggestion[4] that it may be economically desirable to individually process fuel from each reactor at the reactor site. Surface wind trajectories were constructed from each location for successive six-hour periods beginning at 0500Z and continuing for a total travel time of 48 hours. These trajectories were computed for each two-day period from October 11-16th. Further extension was unwarranted since

the trajectories usually moved out of the selected area after 48 hours of travel. More than 400 separate trajectories were computed to estimate the direction of travel and area covered by the assumed effluent from the eight hypothetical sources. Wind speeds and directions recorded at the source were used to compute the first six hours of travel and spread; but for longer travel times the time and space variability of the winds, determined from intermediate observation stations and from meteorological charts, were incorporated in the trajectories. Figure 3 illustrates one series of trajectories for a 36-hour period.

From these trajectories the volume occupied by the effluent from each of the eight hypothetical sources was computed. Such volumetric computations are straightforward but tedious. Horizontal projections of these volumes after 48 hours of travel are shown for selected periods in Figures 4 through 8. These diagrams illustrate the reinforcement of plumes from several sources in specified areas, as a result of time and space variations. Space does not permit inclusion of all the individual trajectories, but most of the computations indicated a reversal of almost 180° in the trajectory (from southwest to northeast) during the movement of the anticyclone across the area.

The results of selected portions of the dilution volume computations and calculated concentrations for specified areas are shown in Table I. The largest volume encompassed for a 48-hour period was 6.8×10^{13} cubic meters by the plume from Hartford, Connecticut (Case 1). A minimum volume 9.26×10^{12} cubic meters was calculated from the plume dimensions of the 48-hour transport and dilution from Philadelphia, Pennsylvania (Case 4). Of the cases in Table I, the first two were chosen to compare the contribution of distant sources to the concentration resulting from the dilution of a nearby source, after six hours of travel. The remaining cases illustrate the cumulative effect of distant sources.

In order to illustrate the implication of this weather situation to the operations of nuclear plants, it was assumed that a 1000 Mw reactor was located at each location from which trajectories were computed. Such a reactor would produce about 1.9×10^{6} curies of $Iodine^{131}$ per day, or 22 curies per second. It is recognized that there is no intention and very little likelihood of emissions of this magnitude ever occurring, either deliberately or accidently. We have assumed that 99.9% of the iodine is removed by decontamination procedures and that the remainder (1.9×10^{3} curies per day) is continuously released at a uniform rate.

Table I also shows the concentrations (curies/$meters^3$) of $Iodine^{131}$ at six locations (Figures 4-8). It can be seen that distant sources can each contribute a relatively large fraction of the total concentration, even in the presence of a direct plume from a nearby source. The average contributions from distant sources range from about 10 to 80 percent of the direct (six-hour) plume concentration. It is recognized that higher concentration values would probably occur at the center of the plume; the concentration values compiled for the six-hour plumes in Cases 1 and 2 represent average concentrations obtained from a unit cross-section. However, there are areas (Cases 3-6) where the cumulative effect of several distant sources produces concentrations of the same order of magnitude as those obtained in Cases 1 and 2.

It should be pointed out that of the eight source locations chosen the two closest sites were separated by 40 nautical miles, and the extreme separation of any two of the eight sites was 240 nautical miles. If it were assumed that one-half the projected electric power generation for this area in 1980 (3.6×10^4 megawatts) were to be produced by nuclear energy, with each reactor producing a thousand megawatts of thermal energy and 250 megawatts of electrical energy, it would take 72 such reactors distributed throughout this area to produce this amount of electricity. If this were the case there would be nine times as many sites as were utilized in this study. If the number of overlapping effluents were directly proportional to the number of sites, and this seems a reasonable assumption, then the cumulative concentrations from the various sites could be much larger than from a direct plume of diffusing material. Consequently if many reactors are to be installed within relatively small areas, very careful site selection and waste disposal measures will be required of all sites to prevent the possible occurrence of undesirable levels of radioactivity. The techniques used for this study are crude, but the lack of refinement was dictated by the impossibility of computing sophisticated models by hand methods. The general procedures outlined here are, however, amenable to high speed computers with much more detail in the diffusion model. Such computers would permit the study of a variety of weather patterns and their interaction with various numbers and spacing of sources. Frenkiel[5] has suggested such an approach on a much smaller scale and the Los Angeles County Air Pollution Control District, Los Angeles, California, Meteorological Section routinely obtain machine-computed trajectories from their wind network.[6]

The situation examined here is one where the atmosphere transported and diluted material rather slowly, but it is not an extreme situation of this type. Much less transport could be expected in other situations or in other geographical areas where similar weather patterns are more frequent and more persistent. This example demonstrates that the widespread utilization of nuclear power could make monitoring of the atmosphere for radioactivity, determination of sources, and the maintenance of acceptable levels of radioactivity exceedingly complex. It is evident that much diligence in control of waste disposal to the atmosphere during stagnant weather conditions will be required, together with the closest cooperation among the operators of all of the various nuclear devices.

REFERENCES

1. Nelson, Federal Power Commission, Washington, D. C., private communication, (March 1958).

2. Korshover, J., Synoptic Climatology of Stagnating Anticyclones East of the Rocky Mountains in the United States for the Period, 1936-1956, United States Weather Bureau, Washington, D. C. (1958).

3. United States Weather Bureau, Meteorology and Atomic Energy, AECU 3066, Washington, D. C., p. 79, (1955).

4. Manly, C. G., Package Processing Plants, paper delivered at Atomic Industrial Forum in New York City, N. Y., (October 28, 1957).

5. Frenkiel, F. N., Atmospheric Pollution in Growing Communities, Annual Report Smithsonian Institute, (1956).

6. Kauper, Erwin; private communication.

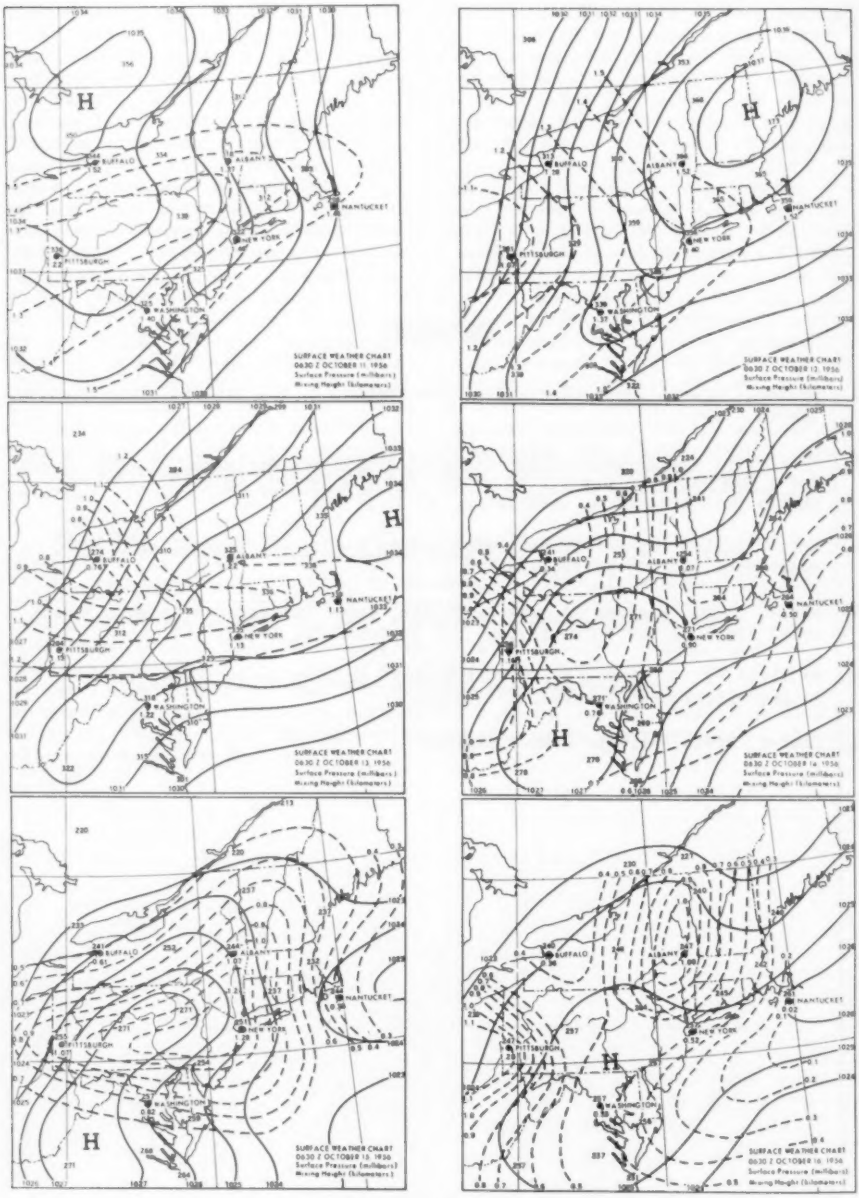

FIGURE 1. SYNOPTIC CHARTS, OCTOBER 11-16, 1956

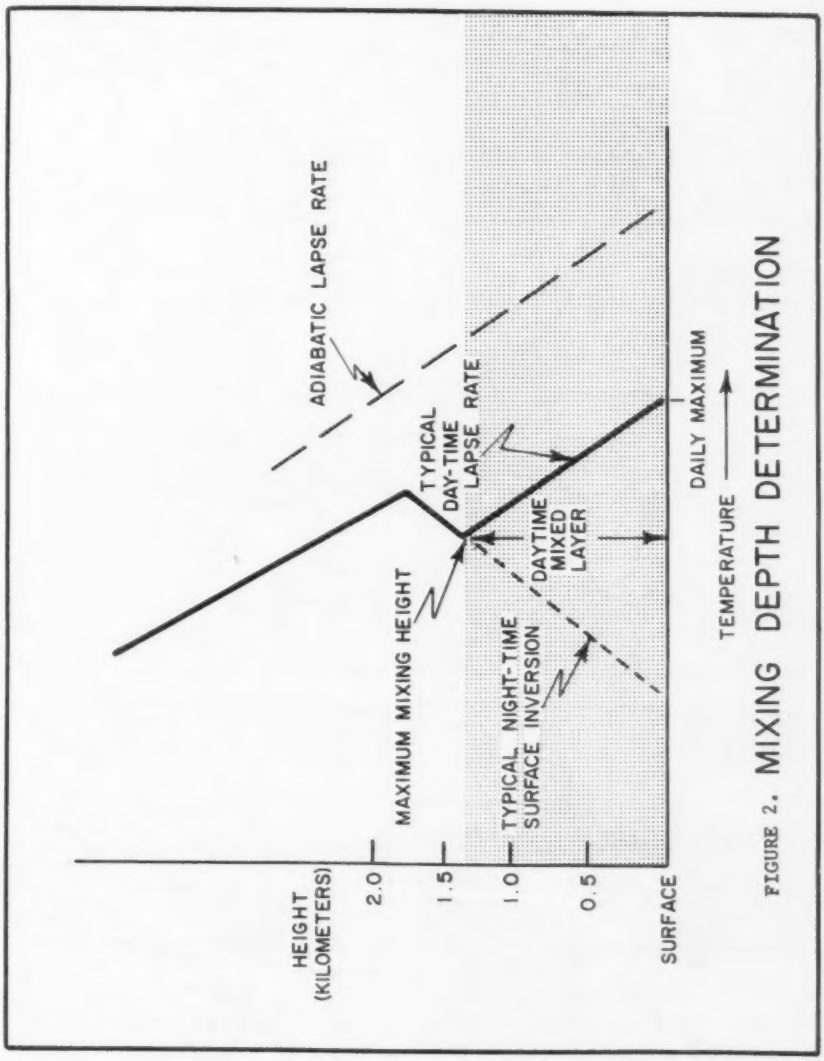

FIGURE 2. MIXING DEPTH DETERMINATION

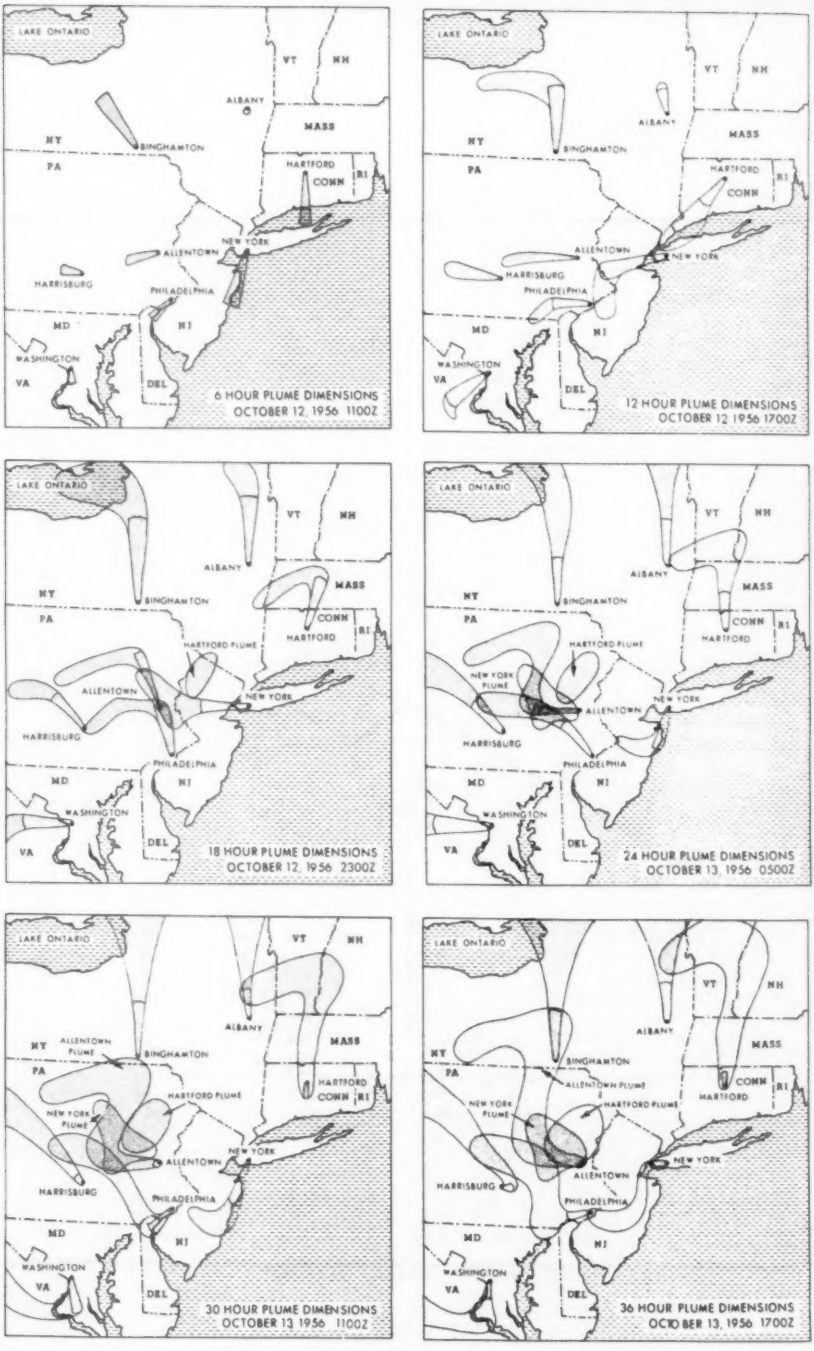

FIGURE 3. TRAJECTORIES FOR A 36-HOUR PERIOD

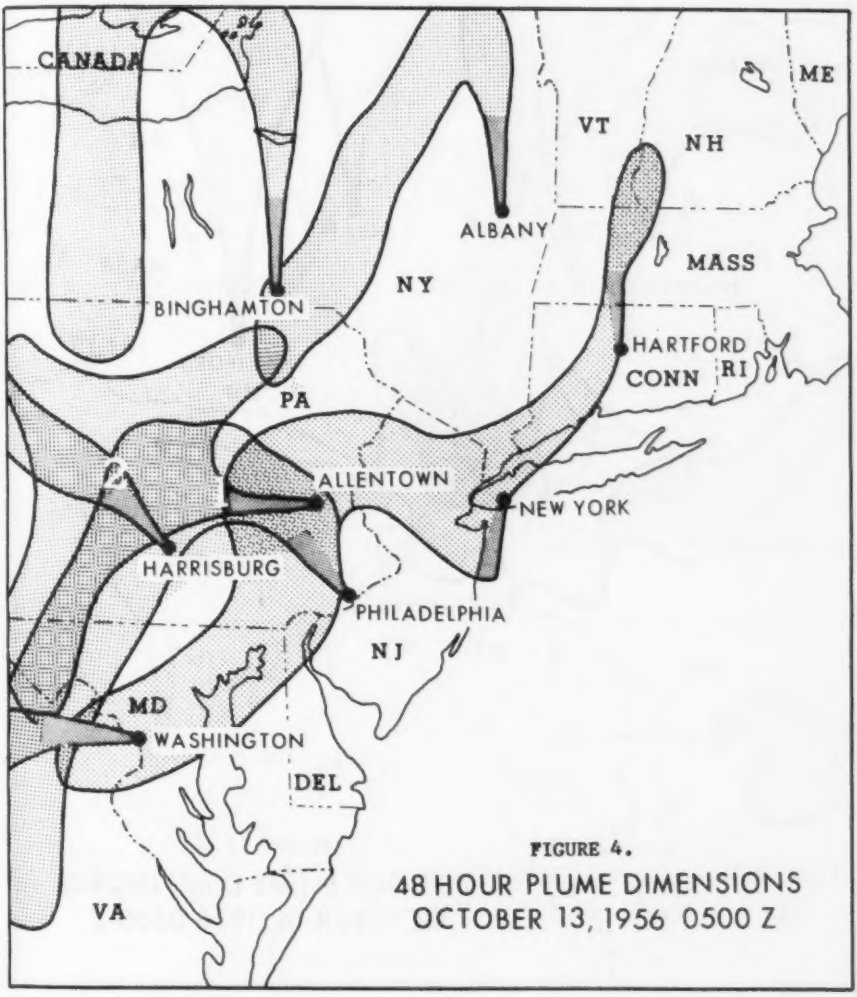

FIGURE 4.
48 HOUR PLUME DIMENSIONS
OCTOBER 13, 1956 0500 Z

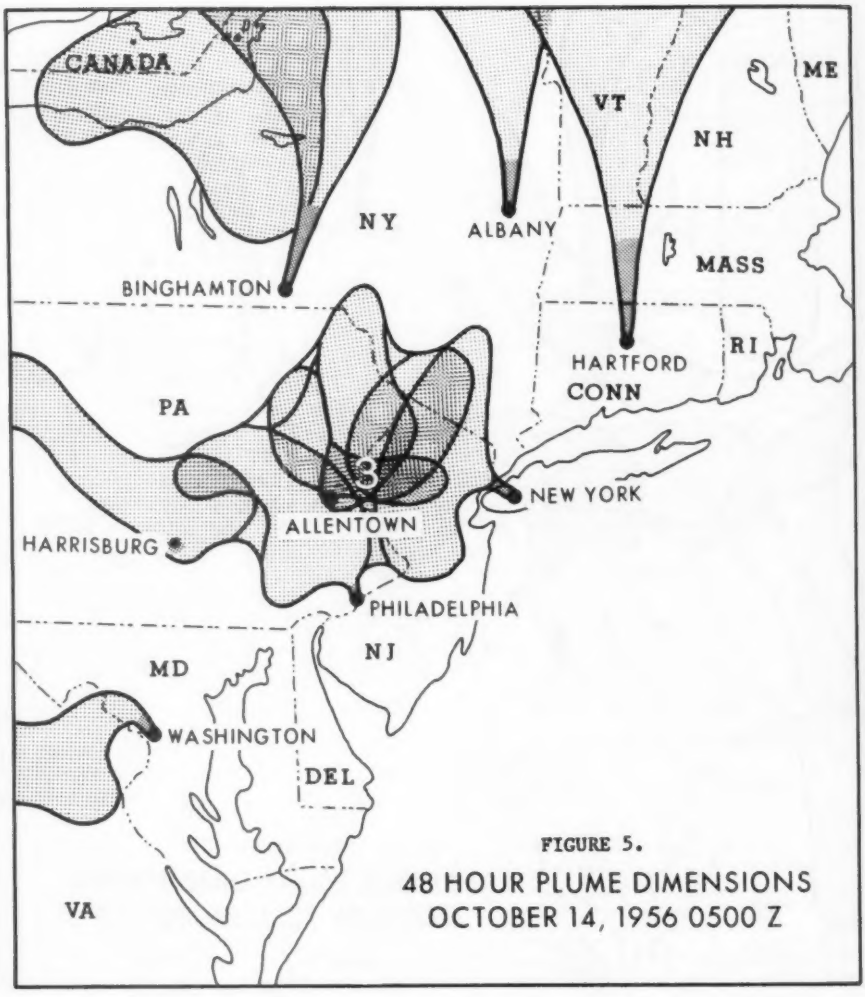

FIGURE 5.

48 HOUR PLUME DIMENSIONS
OCTOBER 14, 1956 0500 Z

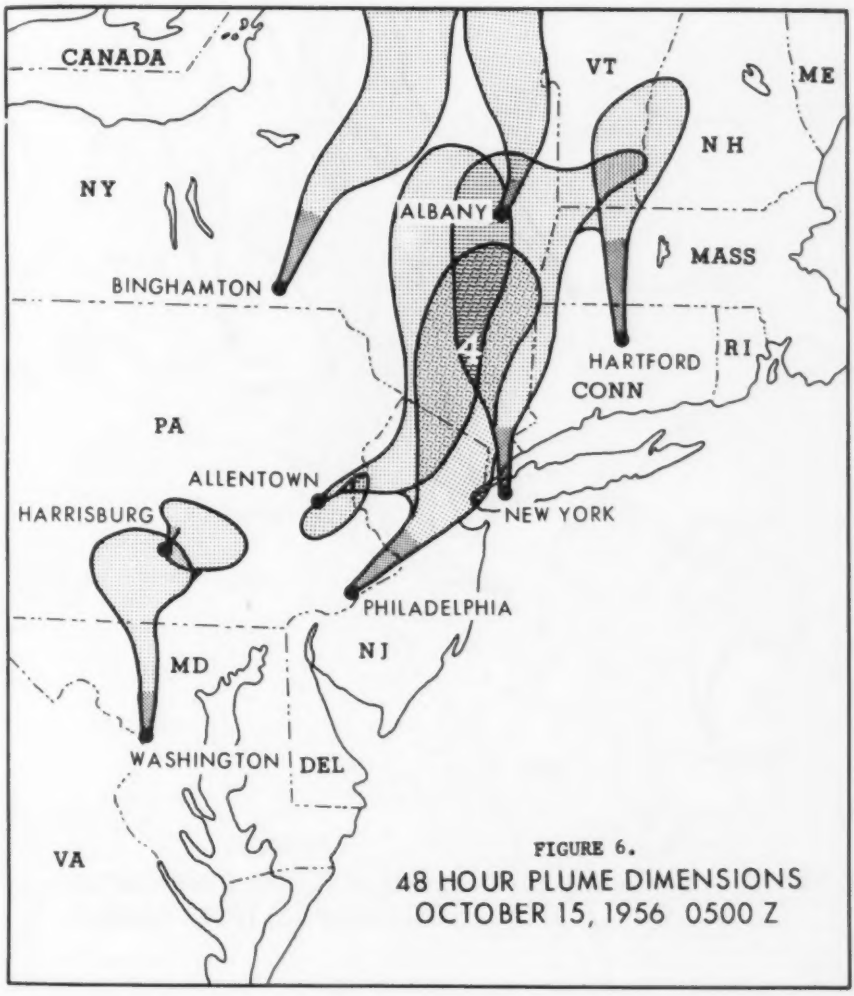
CANADA
VT
ME
NH
NY
ALBANY
MASS
BINGHAMTON
HARTFORD
RI
CONN
PA
ALLENTOWN
HARRISBURG
NEW YORK
PHILADELPHIA
NJ
MD
WASHINGTON
DEL
VA
48 HOUR PLUME DIMENSIONS
OCTOBER 15, 1956 0500 Z

FIGURE 6.

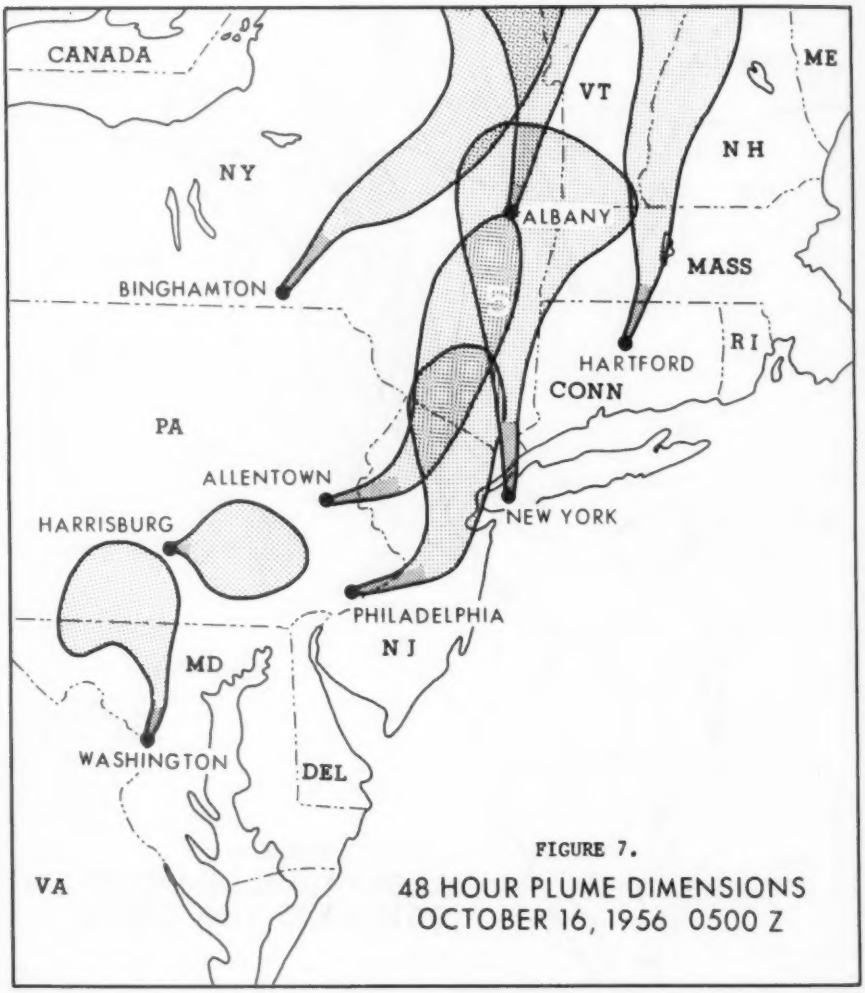

FIGURE 7.

48 HOUR PLUME DIMENSIONS
OCTOBER 16, 1956 0500 Z

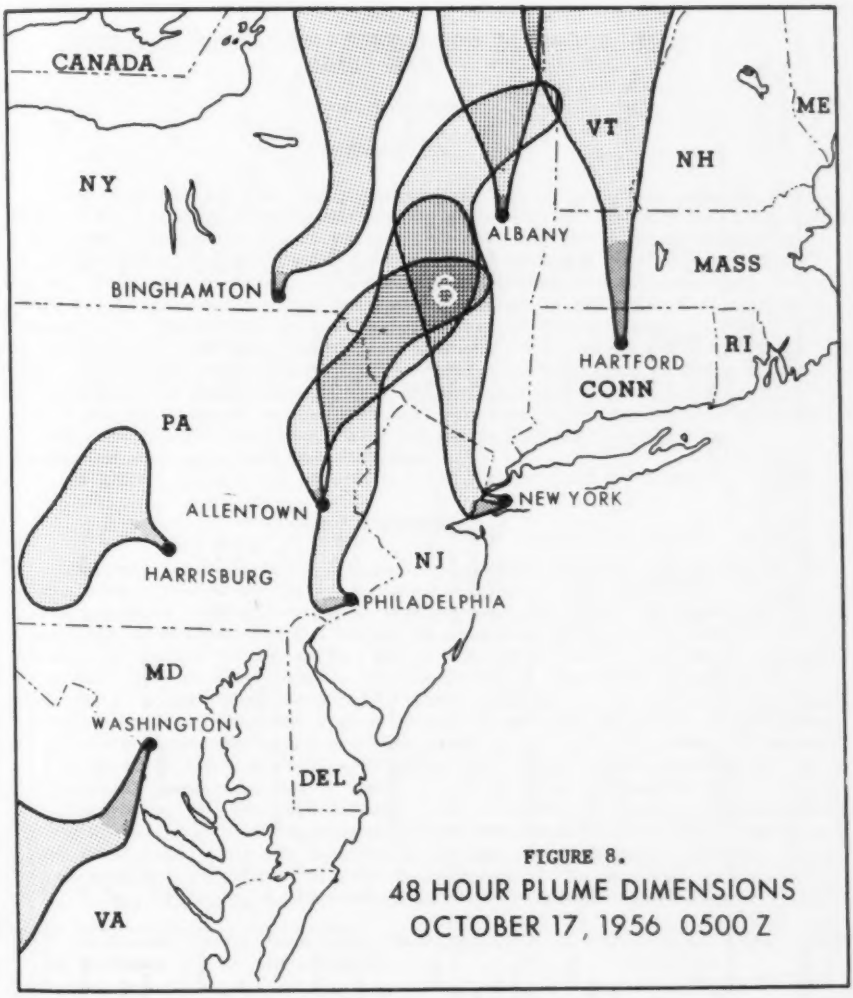

FIGURE 8.
48 HOUR PLUME DIMENSIONS
OCTOBER 17, 1956 0500 Z

TABLE I - COMPUTED POTENTIAL CONCENTRATIONS OF IODINE^{131} FROM HYPOTHETICAL SOURCES

	CASE/REGION	DATE/TIME	PLUME VOLUME (at $\frac{x}{u}$ = t; t = 6 hours)* meters^3	DILUTION VOLUME Travel Time (hours)	DILUTION VOLUME Other Sources meters^3	EMISSION TIME (hours)	SOURCE STRENGTH Curies-I^{131} from 1000 Mw Reactor x Decontamination Factor (10^{-3})	CONCENTRATION (curies/meters^3)	TOTAL CONCENTRATION (curies/meters^3)
1	Allentown, Penna.	Oct 13:0500Z	6.9×10^7			1 sec	2.20×10^{-2}	0.32×10^{-9}	
	Philadelphia, Penna.			24	5.60×10^{12}	18	1.42×10^3	0.25×10^{-9}	
	New York, N. Y.			48	4.89×10^{13}	42	3.32×10^3	0.07×10^{-9}	
	Hartford, Conn.			48	6.80×10^{13}	42	3.32×10^3	0.05×10^{-9}	
									0.69×10^{-9}
2	Harrisburg, Penna.	Oct 13:0500Z	3.0×10^7			1 sec	2.20×10^{-2}	0.73×10^{-9}	
	Allentown, Penna.			48	4.50×10^{13}	42	3.32×10^3	0.07×10^{-9}	
	Philadelphia, Penna.			48	4.89×10^{13}	32	3.32×10^3	0.07×10^{-9}	
									0.87×10^{-9}
3	Allentown, Penna. (30 miles northeast)	Oct 14:0500Z	no effect in this area						
	Allentown, Penna.			48	4.20×10^{13}	42	3.32×10^3	0.08×10^{-9}	
	Hartford, Conn.			48	9.80×10^{12}	15	1.10×10^3	0.12×10^{-9}	
	New York, N. Y.			48	2.60×10^{13}	42	3.32×10^3	0.13×10^{-9}	
	Philadelphia, Penna.			48	1.90×10^{13}	42	3.32×10^3	0.17×10^{-9}	
									0.50×10^{-9}
4	New York, N. Y. (50 miles north)	Oct 15:0500Z	no effect in this area						
	Allentown, Penna.			48	1.10×10^{13}	42	3.32×10^3	0.30×10^{-9}	
	New York, N. Y.			48	1.85×10^{13}	42	3.32×10^3	0.18×10^{-9}	
	Philadelphia, Penna.			48	9.26×10^{12}	42	3.32×10^3	0.36×10^{-9}	
									0.84×10^{-9}
5	Albany, N. Y. (40 miles south)	Oct 16:0500Z	no effect in this area						
	Allentown, Penna.			48	2.01×10^{13}	42	3.32×10^3	0.17×10^{-9}	
	New York, N. Y.			48	1.96×10^{13}	42	3.32×10^3	0.17×10^{-9}	
	Philadelphia, Penna.			48	1.69×10^{13}	42	3.32×10^3	0.20×10^{-9}	
									0.54×10^{-9}
6	Albany, N. Y. (40 miles southwest)	Oct 17:0500Z	no effect in this area						
	Allentown, Penna.			48	1.18×10^{13}	42	3.32×10^3	0.28×10^{-9}	
	New York, N. Y.			48	1.47×10^{13}	42	3.32×10^3	0.23×10^{-9}	
	Philadelphia, Penna.			48	1.16×10^{13}	42	3.32×10^3	0.28×10^{-9}	
									0.79×10^{-9}

* $\frac{x}{u}$ Distance from source - meters
u Average wind speed - meters/hour
t Time - hours

PROGRESS IN APPLICATIONS OF METEOROLOGY TO PEACEFUL USES OF ATOMIC ENERGY

J. Z. Holland*

INTRODUCTION

The requirements for evaluation and control of radiation hazards in connection with the planning and operation of nuclear reactors has provided a powerful stimulus to the development of that branch of meteorology dealing with turbulence, diffusion and local wind patterns in the lower atmosphere. This area of cooperation between meteorologists and scientists of other disciplines had already been well explored by the time of the first International Conference on the Peaceful Uses of Atomic Energy and foundations had been laid for a solid and permanent relationship.[2,3] In the three years since then, substantial progress has been made in three main categories: (1) basic meteorology, (2) applications of meteorological theory and observation to the practical problems of evaluating and minimizing hazards and (3) introduction of automatic methods of procuring and processing meteorological observations.

BASIC METEOROLOGY

The past three years have brought a general reorientation in the study of the dispersion of matter by turbulent eddies in the atmosphere. This period has seen the outgrowing of certain temporarily useful empirical compromise solutions, and the return to fundamental principles which were broadly recognized in the early 1920's. This change has come about through three favorable circumstances: (1) the fruition of earlier pioneering research of a few theoreticians in several countries, (2) the recent sustained attention to these problems over a period of several years by a larger group of theoretical and experimental meteorologists and (3) the gradual acquisition of a body of suitably controlled observational data on the spectrum and structure of turbulence and on quantitative rates of dispersion of matter in the atmosphere. In the United States, and no doubt in other countries as well, the expansion of effort represented by the second and third points has been aided substantially by the demands of the new atomic energy industry. It is now possible for the first time to make use of the profound deductions of G. I. Taylor and L. F. Richardson in their original simplicity.

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G. I. Taylor[4] showed in 1921 that under certain idealized conditions the variance (σ^2) of the spatial distribution of particles released from a fixed point and measured with respect to a fixed axis after a given time of travel would increase with the variance of the turbulent velocity fluctuations and with a function of the travel time which would depend upon the auto-correlation, or persistency, of the eddy velocity fluctuations along particle trajectories. He predicted that at times sufficiently short so that the particle velocity remained significantly correlated with its initial velocity at the point of release σ^2 would increase at first as t^2, the square of the travel time. Ultimately, he deduced, when the eddy motions affecting the particles were no longer significantly correlated with the initial motions (i.e. when σ became larger than the largest dispersing eddies), σ^2 would increase as t, the first power of the travel time. Unfortunately, statistical data on turbulent wind velocity fluctuations were completely lacking, and it was therefore impossible even to set orders of magnitude on the boundaries or transitions between these two regimes.

L. F. Richardson[5], in 1926, showed that the "Fickian diffusion coefficient", of various diffusive processes increased in magnitude rapidly as the scale of the process studied was increased, up to the global - scale mixing processes of the general circulation. This diffusion coefficient is the constant of proportionality between σ^2 and t. The first hope, that σ^2 could be considered proportional to t in most practical applications and that, consequently the theory of molecular diffusion could be applied to turbulent diffusion was thus shattered. Attempts to use this relation in spite of Richardson's findings were unsuccessful. At the same time little consideration was given to the possibility that σ^2 would remain proportional to t^2 over any substantial period after release. Thus the theory gave no practical guidance as to the rate of dispersion of matter from fixed sources over the entire range of dimensions applicable to the problems of air pollution.

Richardson also speculated that the relative spread of pairs of particles moving freely with the wind would depend on different properties of the turbulence than would diffusion from a fixed source, and that the relevant statistics of the motion would involve spatial coordinates rather than time.

Lacking any of the necessary time or space correlations of velocity, O. G. Sutton in 1932 [6] proposed an ingenious formula which had many desirable features. It allowed σ^2 to vary with intermediate powers of t between 1 and 2 depending upon thermal stability, had suitable continuity properties, and incorporated the amplitude of turbulence, the mean wind, and the stabilizing influence of the vertical temperature gradient in a plausible and rather flexible manner. Employing a number of semi-empirical coefficients, this formula has worked reasonably well for the case of a fixed, continuous source, fixed sampling points, travel times ranging from a few seconds to a few minutes, sampling times of the same order, and conditions of nearly neutral atmospheric temperature equilibrium, i.e., primarily

mechanical turbulence. The same formula, however, has been used indiscriminately, with superficial modifications, for all meteorological conditions, for travel times up to tens of hours, for sampling times from seconds to months, and for both relative (moving puff) and absolute (fixed-axis) diffusion. For 10 years, Sutton's formula has been the indispensible tool of the meteorologist in estimating the levels of radioactivity to be expected in the environment of a nuclear plant under the full range of assumed conditions.[3,7]

Even before 1955, theoreticians in several countries had begun to define the significance for diffusion of the various time and space correlations of turbulent eddy velocities and to point out clearly what kinds of measurements were needed. Brier[8] and Batchelor[9] explained the important distinction between relative and absolute diffusion. On the observational side, Barad[10] showed that under inversion conditions, σ^2 appeared to be proportional to t after only a few seconds of travel. Lowry's work,[11] on the other hand, suggested that in moderately turbulent conditions, and for travel times up to several minutes, σ^2 appeared to vary as t^2. Panofsky and McCormick[12] found that vertical turbulence near the ground is more or less lacking in large (low frequency) eddies, particularly in stable (inversion) conditions. A lack of large eddies would favor a rapid transition to the "t" regime. The horizontal component, on the other hand, may contain eddies of all sizes, a situation suggesting "t^2" diffusion.

During the past three years, starting with the scattered suggestions just mentioned, a coherent picture has begun to emerge. The following principles can now be stated with reasonable assurance:

(1) "Relative" diffusion is fundamentally different from "absolute" diffusion. Relative diffusion refers for example to the instantaneous distribution of material in a cloud resulting from an instantaneous release. Absolute diffusion refers to the distribution with respect to a fixed axis oriented along the mean wind, of material which has been emitted continuously at a fixed point over a period sufficiently long to define a mean wind. Relative diffusion depends on spatial correlations of velocity. The character of the space-correlation can be estimated from the "Eulerian" time correlation of wind (measured at a fixed point) by substituting x/u, the distance coordinate divided by the mean wind speed, for the time coordinate t.[13,14]

From the similarity theory of turbulence[15], Obukhov[16] and Batchelor[9] independently deduced that the variance of the distribution measured in relative coordinates with respect to the center of the moving cloud should vary as t^3, the third power of travel time, during the interval when diffusion is dominated by the "inertial subrange" of the eddy spectrum. A study of spectra measured by means of fixed wind instruments suggested to Gifford[17] the possibility that a t^3 variation of σ^2 might be observable in the atmosphere over travel times of the order of a few minutes. Observations have confirmed this surprising prediction.

A t^3 regime does not exist for time-mean concentrations from continuous sources, except perhaps in the case of short-period samples taken in "looping" plumes which are actually broken up into a series of discrete puffs[18].

(2) Absolute diffusion depends upon the Lagrangian autocorrelation function (the serial correlation function of a time-series of wind velocities measured along the trajectory of a freely drifting particle). This can be estimated from the Eulerian autocorrelation by shifting the time dimension of the latter towards lower frequencies by a factor of some 3 to 10[19,20]. This decrease in the apparent duration of eddies is accounted for by their translation past the fixed measuring point. It is found that the diffusion is not highly sensitive to the value of the Lagrangian autocorrelation. For the time period over which it remains significantly positive (greater than, say, 0.2), the variance of the distribution of diffusing matter from a continuous point source is directly proportional to the variance of the wind direction at the source. This direct prediction of σ^2 from wind variance is found to be applicable over travel times of the order of several minutes, i.e. distances of the order of kilometers, in lapse or neutral conditions[11, 18, 20, 21]. This is also sometimes true of the horizontal but not the vertical distribution in inversion conditions[22].

(3) Vertical diffusion near the ground is fundamentally different from horizontal diffusion in that the vertical eddy size is bounded by the height and also, in inversion conditions, by the stability. The eddies in inversions have only short periods when measured at a fixed point, and are evidently also relatively non-persistent, so that the autocorrelation of vertical velocity along a particle trajectory quickly drops to zero. Thus a regime in which the vertical σ^2 varies as t with a constant, small, coefficient (the "Fickian" diffusion coefficient) appears to be the rule from a few seconds on during stable conditions. The horizontal turbulence may or may not contain large eddies and will therefore sometimes produce a "Fickian" diffusion regime in inversions, depending upon the spectrum of lateral, or "cross-wind" eddy components[22].

To summarize the progress in basic meteorology, studies of turbulence spectra, and of more detailed and accurate diffusion measurements than were previously available, have led to more meaningful restatements of the basic theories developed over thirty years ago. The intermediate period has been characterized by semi-empirical equations employing adjustable powers of time. These are being replaced by equations which are simpler from the computational standpoint, which contain explicitly measurable meteorological parameters, and which have a more rigorous theoretical basis. This has come about through the discovery that limiting cases of the general equations can be utilized over a wider range of conditions, and transitional regimes are less dominant than was formerly supposed.

Much more remains to be done in defining the criteria for transition from one regime to another, and in obtaining a comparable insight into phenomena occurring on time scales of the order of hours and days.

The various laboratories in the United States have gained experience in making diffusion measurements using many tracer materials. Sulfur dioxide has been used by the Round Hill Field Station of Massachusetts Institute of Technology at "Project Prairie Grass" in Nebraska in 1956 for unusually detailed sampling over a range of half a mile[18]. Sulfur dioxide, present in the stack gases from power plants, is also being sampled by the Tennessee Valley Authority in three dimensions over distances up to 40 miles by the use of helicopters[23].

Oil fog has been used by the Brookhaven National Laboratory for quantitative measurements to several miles and for qualitative indications to 30 miles[24]. Techniques for quantitative analysis of smoke photographs have been developed at the Argonne National Laboratory and at the Weather Bureau Office in Oak Ridge[17] which may make visible tracers more useful for scientific research.

A new method of gamma-ray scanning has been used to obtain measurements on radioactive plumes from reactors and chemical processing plants at the National Reactor Testing Station in Idaho.

The fluorescent particle technique has been used at Hanford over distances of several miles[22] to provide detailed information on both instantaneous and time-mean concentrations, and for studies of pickup and translocation of deposited material[25]. Measurements are planned at greater distances.

As each of these techniques is extended to distances of many miles not only the sensitivity of detection but also the horizontal area and vertical depth over which sampling devices must be distributed impose increasingly severe problems. Nevertheless, the prospect of obtaining improved information for predicting the consequences of the spread of radioactivity over large areas appears to be good.

APPLICATIONS TO ATOMIC ENERGY PROBLEMS

Last year the Atomic Energy Commission, with the assistance of the Brookhaven National Laboratory and the advice of a large number of experts throughout the country, prepared a study of "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants"[26]. Generally accepted methods of meteorological analysis were employed. A number of individual treatments of this same general problem containing various refinements can be mentioned.

Fitzgerald[27] has corrected the overestimates of radiation from fallout due to use of an infinite-area formula to represent small contaminated areas. Gomberg[28] has evaluated external and internal radiation separately,

and has obtained weighted average numbers of people affected at various dose levels by the use of actual population distributions and climatological frequencies of the meteorological variables for two specific sites. Healy[29] has made more detailed use of recent information on fractionation of fission products by volatility in accidents of various energies, and has also employed the latest Hanford formulations of diffusion in inversions and British data on surface deposition rates. Leonard[30] has introduced non-isotropic powers of distance in the Sutton formula, using coefficients obtained by analysis of the TVA helicopter data. Menegus and Ring[31] have given general methods for computing the probability of lethal doses occurring due to inhalation, cloud radiation, or sudden deposition of a cloud of reactor fission products by a rain shower.

Lubarsky[32] of the National Advisory Committee on Aeronautics has worked the diffusion equation in reverse to calculate the maximum permissible rate of leakage from a reactor containment building under specified accident conditions. This leakage rate will not result in a quarter-year dose at any location in the environment exceeding the permissible limit, assuming that the relevant meteorological conditions occur with their normal climatological frequency during the period.

In addition to these general or methodological studies, each particular reactor approved for construction or operation has been evaluated in terms of the environmental levels of radioactivity estimated to result from normal operation or from any credible malfunction. In these evaluations, the choice of meteorological parameters and formulae often plays an important part.

AUTOMATIC METHODS OF OBSERVATION AND DATA PROCESSING

Recent intensified efforts by instrument manufacturers to produce highly reliable industrial data handling systems have produced enough commercially available building blocks to allow the assembly of a great variety of specialized data systems. The lowered cost of automatic or semi-automatic data acquisition and processing systems now renders their use for micrometeorological networks highly advantageous in comparison to the time and manpower requirements for manual chart reading. In the major reactor facilities of the Atomic Energy Commission, this trend is well advanced.

Meteorological observations are combined in some cases with automatic reporting of radioactivity data from outlying locations. In addition to economy in research and operational documentation, such systems have the advantage of immediate availability of necessary information in the event that action may be required to protect the public health and safety. Synchronization, intercalibration, and early detection of malfunction are also facilitated.

At Oak Ridge, electrical signals representing wind direction, wind speed, temperature, dew point, vertical temperature gradient and precipitation are transmitted automatically over telephone lines several times each hour from five stations, converted to digital coded impulses and printed by a conventional teleprinter[3]. For analysis and permanent file, the data are stored on punched cards, tabulated and summarized by machine, and filed in the form of photographically reduced "microcards".

A similar system, including radioactivity measurements and providing surveillance to some 50 miles off-site, is in operation at the National Reactor Testing Station in Idaho.

At the Brookhaven National Laboratory a rapid scanning system is being installed for putting all recorder outputs on a tape for automatic analysis or statistical treatment. Another unit automatically converts current measurements of wind direction, wind speed and gustiness to the parameters of effluent concentration distribution. This information is continuously available to both the reactor operator and the meteorologist.

The Argonne National Laboratory is now in process of installing automatic meteorological data processing equipment. One part of the system which has been in operation for several months provides hourly soil temperatures at seven depths.

At Hanford a network is in process of being installed which will consist of twenty stations each of which will be capable of reporting wind direction, wind speed and radiation levels, each averaged over 5, 15, 30 or 60 minutes. The telemetering will be by radio and the output will be in two forms: a numeric tabulation for immediate use and a computer tape for completely automatic summarizing, storage and selection.

Extensive use is also being made of both analog and digital computers in turbulence spectrum analysis, comparison of different diffusion models, and parametric studies of environmental effects as a function of reactor, population and meteorological parameters.

The more efficient acquisition and processing of research and operational data by automatic methods will undoubtedly contribute greatly both to the future advancement of the basic theory of atmospheric diffusion, and to the application of meteorological knowledge to the practical problems of atomic energy.

FOOTNOTES

(1) Contributors: H. E. Cramer (Massachusetts Institute of Technology Cambridge, Mass.), B. Davidson (New York University New York, N.Y.), F. E. Gartrell (Tennessee Valley Authority, Chattanooga, Tenn.), F. Gifford, Jr. (U.S. Weather Bureau, Oak Ridge, Tenn.), J. Halitsky (New York University, New York, N.Y.), G. R. Hilst (General Electric Co., Richland, Wash.), H. F. Islitzer (U.S. Weather Bureau, Idaho

Falls, Idaho), B. Lubarsky (National Advisory Committee for Aeronautics, Cleveland, Ohio), R. McCormick (U.S. Weather Bureau, Washington, D. C.), R. L. Menegus (E. I. duPont de Nemours & Co., Wilmington, Del.), H. Moses (Argonne National Laboratory, Lemont, Ill.), R. F. Myers (U.S. Air Force Cambridge Research Center, Bedford, Mass.), D. H. Pack (U.S. Weather Bureau, Washington, D. C.), H. A. Panofsky (Pennsylvania State College, State College, Pa.), M. E. Smith (Brookhaven National Laboratory, Upton, N.Y.), I. Van der Hoven (U.S. Weather Bureau, Las Vegas, Nev.).

(2) Wexler, H., Machta, L., Pack, D. H., and White, F.D., Atomic Energy and Meteorology", Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, United Nations, 1956.

(3) U.S. Weather Bureau, Meteorology and Atomic Energy, U.S. Government Printing Office, 1955.

(4) Taylor, G.I., Diffusion by Continuous Movements, Proc. Lond. Math. Soc., 20, pp. 196-212, 1921.

(5) Richardson, L.F., Atmospheric Diffusion Shown on a Distance-Neighbor Graph, Proc. Roy. Soc. Lond. A,110, 756, pp. 709-737, 1926.

(6) Sutton, O.G., A Theory of Eddy Diffusion in the Atmosphere, Proc. Roy. Soc. Lond., A, 135, pp. 143-165, 1932.

(7) Beers, N.R., Stack Meteorology and Atmospheric Disposal of Radioactive Waste, Nucleonics, 4, pp. 28-38, 1949.

(8) Brier, G. W., The Statistical Theory of Turbulence and the Problem of Diffusion in the Atmosphere, J. Meteor., 7, pp. 283-290, 1950.

(9) Batchelor, G. K., Diffusion in a Field of Homogeneous Turbulence, II. The Relative Motion of Particles, Proc. Cambridge Phil. Soc., 48, pp. 345-362, 1952.

(10) Barad, M.L., Diffusion of Stack Gases in Very Stable Atmospheres, Meteor. Monographs, 1, No. 4, pp. 9-14, 1951.

(11) Lowry, P.H., Microclimate Factors in Smoke Pollution from Tall Stacks, Meteor. Monographs, 1, No. 4, pp. 24-29.

(12) Panofsky, H.A., and McCormick, R.A., Properties of Spectra of Atmospheric Turbulence at 100 m, Quart. J. Roy. Meteor. Soc., 80, pp. 546-564, 1954.

(13) Gifford, F., Jr., The Relation Between Space and-Time Correlations in the Atmosphere, J. Meteor., 13 pp. 289-294, 1956..

(14) Ogura, Y., The Relation Between the Space-and Time-correlation Functions in a Turbulent Flow, J. Meteor. Soc. Japan, 31, pp. 355-369, 1953.

(15) Batchelor, G.K., The Theory of Homogeneous Turbulence, London, Cambridge Univ. Press, 475 pp., 1953.

(16) According to Yudin, M.I., Physical Mean-forming and the Laws of Turbulent Diffusion, Comptes Rendus (Doklady), 51, pp. 103-106, 1946.

(17) Gifford, F., Jr., Relative Atmospheric Diffusion of Smoke Puffs, J. Meteor., 14, pp. 410-413, 1957.

(18) Cramer, H. E., A Practical Method for Calculating the Dispersal of Atmospheric Contaminants, Paper presented at the First National Conference on Applied Meteorology, Hartford, Conn., 1957.

(19) Gifford, F., Jr., A Simultaneous Lagrangian-Eulerian Turbulence Experiment, Monthly Weather Review, 83, pp. 293-301, 1955.

(20) Hay, J.S., and Pasquill, F., Diffusion from a Fixed Source at a Height of a Few Hundred Feet in the Atmosphere, J. Fluid Mech., 2, pp. 299-310, 1957.

(21) Davidson, B. and Halitsky, J., A Method of Estimating the Field of Instantaneous Ground Concentration from Tower Bivane Data, J. Air Pollution Control Assoc., November, 1957.

(22) Hilst, G.R., The Dispersion of Stack Gases in Stable Atmosphere, J. Air Pollution Control Assoc., November, 1957.

(23) Gartrell, F.E. and Carpenter, S.B., Aerial Sampling by Helicopter: a Method for Study of Diffusion Patterns, J. Meteor., 12, No. 3, 1955.

(24) Smith, M.E., The Variation of Effluent Concentrations from an Elevated Point Source, Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, United Nations, 1956.

(25) Healy, J.W. and Fuquay, J.J., Wind Pickup of Radioactive Particles from the Ground, paper prepared for the Second International Conference on the Peaceful Uses of Atomic Energy, 1958.

(26) U.S. Atomic Energy Commission Document WASH-740, Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants, 1957.

(27) Fitzgerald, J.J., Modifications, Improvements and Simplifications of Environmental Reactor Hazards Evaluations, paper prepared for Second International Conference on the Peaceful Uses of Atomic Energy, 1958.

(28) Gomberg, H.J., A Quantitative Approach to Evaluation of Risk in Locating a Reactor on a Given Site, paper prepared for Second International Conference on the Peaceful Uses of Atomic Energy, 1958.

(29) Healy, J.W., Calculations on Environmental Consequences of Reactor Accidents Interim Report, U.S. A.E.C. Document HW-54128, 1957.

(30) Leonard, B.P., Hazards Associated with Fission Product Release, paper prepared for Second International Conference on the Peaceful Uses of Atomic Energy, 1958.

(31) Menegus, R.I. and Ring, H.F., Accidental Dispersion of Reactor Poisons and the Controlled Distance Required, U.S. A.E.C. Document DP-105 (Rev. 2), 1958.

(32) National Advisory Committee for Aeronautics, NACA Reactor Facility Hazards Summary, Supplements IV and V, Cleveland, Ohio, 1957.

Representative HOLIFIELD. Our next witness will be Dr. Leslie Silverman, of Harvard, who will present testimony on air cleaning. He is our last witness for today.

STATEMENT OF LESLIE SILVERMAN,[12] SC. D., PROFESSOR OF ENGINEERING IN ENVIRONMENTAL HYGIENE, DIRECTOR OF RADIOLOGICAL HYGIENE PROGRAM, HARVARD UNIVERSITY

Mr. SILVERMAN. Mr. Chairman, I find myself in a slightly awkward position here because usually we try to clean the air before we give it to meteorologists. Now I find that we have to describe how to clean it up after the meteorologists.

In this presentation I am going to perhaps depart somewhat from my prepared statement but I will let you know when.

Air and gas cleaning for nuclear energy processes differs from general cleaning problems in two major respects. One is the high order of toxicity of the contaminants, and in the second the cleaning device becomes dangerously contaminated and thus poses health problems due to radiation or disposal of collected materials. Radioactive gases and particulate matter in solid or liquid forms are the basic cleaning problems. Because of their high toxicity the degree of cleaning necessary is much more severe than for most non-radioactive materials.

Air- and gas-cleaning problems arise from the mining, refining, and production of uranium and thorium. In providing cooling air for reactors or for shielding, contamination results from induced radioactivity in particulates conveyed by the cooling air if it is not well precleaned. Cooling air may also become contaminated with radioactive gases or particulates resulting from failure or from erosion of fuel elements.

Processing of reactor elements or slugs results in gaseous and particulate emanations from fission products, which create radioactive

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[12] Born in Chicago in 1914. Graduate in mechanical engineering from University of Illinois; M.S. in mechanical engineering from Rutgers University; S.M. and Sc. D. in industrial hygiene engineering from Harvard University.

At Harvard since 1937 in various capacities and at present time professor of engineering in environmental hygiene at Harvard University School of Public Health, and division of engineering and applied physics, Graduate School of Arts and Sciences (director of radiological hygiene program).

Consulting engineer in air pollution control, industrial hygiene and industrial ventilation. Registered professional engineering in Massachusetts. Certified America Sanitary Engineering Intersociety Board, 1957. Diplomate, American Academy of Sanitary Engineers.

Present research on air and gas cleaning, aerosol behavior, radiological hygiene and industrial ventilation.

Member of A.S.M.E. A.I. Ch. E., A.A.A.S., A.S.E.E., A.P.C.A., A.S.T.M., American Industrial Hygiene Association, the Health Physics Society, American Nuclear Society, ASTM. Tau Beta Pi and Sigma Xi. Director AIHA, 1957–.

Member of technical and advisory committees: U.S. Atomic Energy Commission—member, Advisory Committee on Reactor Safeguards, National Research Council, National Academy of Science, U.S. Public Health Service, American Society for Testing Materials, American Standards Association, American Public Health Association, National Bureau of Standards, and American Society of Mechanical Engineers. Chairman: D–22 Committee—ASTM; Subcommittee on Atmospheric and Industrial Hygiene—NRC. Member—Division of Toxic. and Ind. Hyg., International Union Pure and Applied Chemistry.

Author of "Industrial Air Sampling and Analysis," "Handbook on Air Cleaning," and over 200 articles in technical journals on industrial hygiene, ventilation, air analysis, air pollution control, and radiological hygiene. Eight United States and foreign patents granted, 5 pending.

Army-Navy Certificate of Appreciation for services in World War II, 1947.

Award for design, Lincoln Arc Welding Foundation, 1947.

Clemens Herschel prize, Boston Society of Civil Engineers, 1955.

Technical delegate, U.S. State Department, Atoms-For-Peace Conference, Geneva, Switzerland, 1955.

See also: "Who's Who in Engineering," sixth, seventh, eighth edition "American Man of Science," eighth, ninth edition (physical science).

aerosols requiring nearly complete removal from the air stream before discharge to the atmosphere. Laboratory and pilot production of special isotopes and metals, recovery of certain materials, and isotope separation processes are operations which create radioactive contaminants.

Reduction of bulk volume of waste by incineration or evaporation of liquids each day may create airborne particulates which require special treatment. The air and gas cleaners by their recovery function provide solid- or liquid-contaminated materials which must be processed or handled. The contaminants range from rare gases, such as argon (A^{41}), which are difficult to recover, to highly corrosive acid gases from metal extraction processes, such as hydrogen fluoride (HF). Solid and liquid particulates may be organic or inorganic and may range in size from less than 0.05μ to 20μ. The finest particulates arise from metallurgical fumes evolved by burning or vaporization, and the coarsest are acid-mist droplets.

The purpose of this presentation is to give the highlights of the general program on air and gas cleaning research and development which has been conducted at Harvard under AEC sponsorship through its Division of Reactor Development since February 1950. A 2-year preliminary study on fundamental information and approaches to air cleaning was undertaken for the New York Operations Office in 1948–50. The overall project has thus been under active investigation for approximately 10 years.

Scope and functions: The scope and functions of the Harvard Air Cleaning Laboratory are in the fields of consultation, research, and development. Our laboratory and field work can be best described under five main objectives:

1. Our major responsibility is to perform research and develop new procedures or modifications of existing approaches to solve nuclear energy gaseous waste problems. These are either brought to our attention by consultations with various site personnel or are conceived by us as approaches to basic problems associated with production, fixation, and recovery processes.

2. We serve as a consulting as well as a correlating and collating agency to bring together information on air and gas cleaning problem approaches for the national laboratory sites and other contractors. This information is then disseminated by means of field trip reports, seminars (discussed later under 5), or reference handbooks such as the "Handbook on Air Cleaning."

3. There are many air and gas cleaning problems that develop in new neuclear energy applications. We are often requested to provide evaluation of equipment for an AEC application on an unbiased basis. The Atomic Energy Commission through its contractors purchases a considerable amount (millions of dollars per year) of air and gas cleaning equipment, some of which may be new and untried, or have to be adapted to special purposes. For new or relatively untried devices we have upon AEC request only supplied test evaluations as to their merits. We do not consider this a primary function, but serve in this regard when asked to provide an unbiased opinion concerning equipment performance on aerosols or under conditions peculiar to AEC needs.

4. In relation to the above type of laboratory investigation, it is necessary to follow such studies in the field; therefore, we are concerned with the development of suitable test methods and evaluation procedures for performance under many unusual conditions.

5. We provide, upon request, training and education for AEC or contractor personnel by assignment to our laboratory, by consultations and discussion with various contractor organizations and groups. In this connection, we have held a number of information seminars, both classified and unclassified. The sixth one is scheduled for this year.

I have a copy here of the fifth air cleaning seminar presentation, and this is perhaps by way of answer to Mr. Bates' earlier question as to how we get information out to the people who can use it. These seminars serve that purpose.

These seminars are for interested contractor personnel who have related problems in the air and gas cleaning field. The last seminar (fifth) for the first time was opened to access permit holders. A typical example of one of the air cleaning seminar programs is shown in figure 1. These seminars give us an opportunity to acquaint those in the field with new developments and to provide information and data on items pertinent to certain problems. A limited number of personnel from various sites also spend time at our laboratory to become familiar with new evaluation techniques and approaches.

FIGURE 1.—Program

FIFTH AIR CLEANING SEMINAR, HARVARD SCHOOL OF PUBLIC HEALTH, AIR CLEANING LABORATORY, BOSTON, MASS., JUNE 24–27, 1957

JUNE 24, 25—REVIEW SESSION

JUNE 26—REVIEW OF SITE ACTIVITIES

9:15 a.m.: Introduction and welcome	Dr. J. A. Lieberman, USAEC, Prof. Leslie Silverman, HSPH.
(Chairman, morning session, Dr. Joseph A. Lieberman)	
9:30–9:45 a.m.: Particulate airborne contamination at startup of the experimental boiling water reactor.	J. J. Hartig, Argonne National Laboratory.
9:45–10 a.m.: Summary of the air cleaning activities at the Argonne National Laboratory.	D. P. O'Neil, Argonne National Laboratory.
10–10:15 a.m.: Meteorological program at Brookhaven National Laboratory.	R. Brown, Brookhaven National Laboratory.
10:15–10:30 a.m.: Summary of air cleaning activities at Brookhaven National Laboratory.	R. Brown, Brookhaven National Laboratory.
10:30–10:45 a.m.: Summary of air cleaning activities of Brush Beryllium Co.	H. J. Shafer, Brush Beryllium Co.
10:45–11 a.m.: Summary of air cleaning activities of the Beryllium Corp.	A. Epstein, Beryllium Corp.
11:00–11:15 a.m.: To be announced	R. T. Smith–K–25, Oak Ridge National Laboratory.
11:15–11:30 a.m.: Summary of Los Alamos air cleaning activities.	H. S. Jordan, Los Alamos Scientific Laboratory.
11:30 a.m.–1:15 p.m.: Lunch.	
(Chairman, afternoon session, Dr. Abel Wolman)	
1:15–1:30 p.m.: Summary of air cleaning activities at Oak Ridge National Laboratory.	F. M. Empson, Oak Ridge National Laboratory.
1:30–1:45 p.m.: Summary of air cleaning activities at Savannah River operations.	To be announced.

FIGURE 1.—Program—Continued

JUNE 26—REVIEW OF SITE ACTIVITIES—continued

1:45–2 p.m.: Summary of AEC Bettis Plant air cleaning activities.	P. Bolton and J. E. Ross, Westinghouse, APD.
2–2:15 p.m.: A summary of the air cleaning experience at naval reactor facility.	J. Horan, Westinghouse, NRF.
2:15–2:30 p.m.: Air cleaning activities at the GE–ANP Idaho Test Station.	R. M. Chatters, General Electric, ANP.
2:30–2:45 p.m.: Air cleaning activities at Mallinckrodt Chemical Works.	W. Utnage, Mallinckrodt Chemical Works, Uranium Division.
2:45–3:00 p.m.: Air cleaning activities at Knolls Atomic Power Laboratory.	W. H. Truran, Knolls Atomic Power Laboratory.
3:00–3:15 p.m.: Air cleaning activities at Atomics International.	A. A. Jarrett, Atomics International.
3:15–3:30 p.m.: Air cleaning activities at Goodyear Atomic Corp.	B. Kalmon, Goodyear Atomic Corp.
3:30–4:00 p.m.: Developments in the manufacture of absolute filters.	P. M. Engle, Cambridge Filter Corp., A. R. Allan, Jr., Flanders Mill, Inc.; R. A. Bub, Mine Safety Appliances Co.
4:00–4:45 p.m.: Panel discussion, Fire resistant filter progress at Hanford.	F. E. Adley, Hanford APD, GE; J. H. Palmer, Hanford APD, GE; D. J. Kiegher, Hanford Op., AEC.
Moisture and burning tests on space filters	J. H. Palmer.
4:45 p.m.: Discussion	

JUNE 27—NEW DEVELOPMENTS

(Chairman, morning session, Prof. Philip Drinker)

9:00–9:15 a.m.: An improved cascade impactor.	R. Mitchell and M. Pilcher, Battelle Memorial Institute.
9:15–9:30 a.m.: A multibed low velocity air cleaner.	R. E. Yoder and F. M. Empson, Oak Ridge National Laboratory, X–10.
9:30–10:00 a.m.: Air cleaning experience with radioactive I^{131} in the gas phase.	M. D. Thaxter, University of California Radiation Laboratory.
10:00–10:30 a.m.: Aerosol exposures associated with nuclear fuel element fabrication.	M. Mason, Mallinckrodt Chemical Works, Uranium Division.
10:30–10:45 a.m.: Intermission.	
10:45–11:00 a.m.: Economic survey of air and gas cleaning operations within the Atomic Energy Commission—Progress report.	R. Dennis, Harvard University, Air Cleaning Laboratory.
11:00–11:15 a.m.: Air cleaning costs, a study of three systems.	H. S. Jordan, Los Alamos Scientific Laboratory.
11:15–11:30 a.m.: New developments at the University of Illinois.	H. F. Johnstone, University of Illinois.
11:30–1:15 p.m.: Lunch	

(Chairman, afternoon session, Dr. Leslie Silverman)

1:15–2:00 p.m.: Review of air cleaning studies at Harvard University.	L. Silverman, Harvard University, Air Cleaning Laboratory.
2:00–2:30 p.m.: High temperature gas cleaning.	C. E. Billings, Harvard University, Air Cleaning Laboratory.
2:30–2:45 p.m.: Slag wool as an acid gas and mist filter.	C. Kurker, Jr., Harvard University, Air Cleaning Laboratory.
2:45–3:00 p.m.: Agglomeration of particulate materials.	E. C. Hickey, Harvard University, Air Cleaning Laboratory.
3:00–3:30 p.m.: Development of a "triboelectrified" fluidized bed for aerosol filtration.	D. M. Anderson, Harvard University, Air Cleaning Laboratory.
3:30–3:45 p.m.: Filtration of fume from sodium-potassium metal.	E. Kristal, Harvard University, Air Cleaning Laboratory.

Kinds of problems under active study: It is rather interesting to point out the basic changes in thinking in this field in the 10 years since we have been involved in air- and gas-cleaning investigations for the AEC. In the early days, wet collectors and scrubbers were considered as ideal for collecting the particulate matter, dust, fumes, and so forth, as an aqueous suspension which could then be readily piped to the liquid waste disposal plant for treatment and storage. We were told that it was easy for the laboratory people to handle the problem. They put in a wet collector, caught the waste gases and particulates, and then let the waste-disposal people worry about it. Now we find the waste problem has reached the point of no return and it is now necessary to convert the stored liquids in solid wastes. This conversion means production of aerosols, fumes, and mists with their attendant air-cleaning problems. Thus, the problem has never been really solved but merely bypassed temporarily. As you know, a certain amount of liquid storage will be necessary until other techniques become available. Wet collector performance actually has left much to be desired since corrosion, carryout, inefficiency, plugging, and other problems encountered in practice has made it desirable in many instances to substitute dry collection.

In AEC philosophy, as we interpret it for air- and gas-cleaning problems, the importance of containment has always remained paramount. Active materials must be placed in situations from which they cannot be disseminated and expose either operating personnel or the public. Hence, when considering the question of gas cleaning or air cleaning we believe it is paramount that the process should be modified so that gas or air volumes produced are kept as low as possible. Much of our effort in research and development has been to reduce the volumes of gases to be cleaned. Some of the gas volumes involved may be as small as fractions of a cubic foot per minute. Even in these small volumes large amounts of radioactivity may be involved.

The next figures (figs. 2 and 2A) show the type of aerosol generating and sampling apparatus we have to develop in order to evaluate some of the equipment I mentioned a few minutes ago.

Our current investigations center around several major studies: The first is to develop an inexpensive method for the removal of iodine from effluents of reactors and chemical processing plants. This is to provide us with information so that situations as that which occurred at Windscale will not happen here. In this regard we have developed an inexpensive low flow resistance silver-plated copper gauze.

There is a sample of this material placed on your table. It happens to be a Chore Girl scouring pad which was the simplest copper mesh we could obtain locally (fig. 3). We found that the copper was a cheaper and better fixation media for iodine but the trouble was we could not be sure of its life because copper when allowed to stand will oxidize. Whether or not it would interfere with its iodine removal was important. By applying a silver plate to it provides protection in depth. It will work at temperatures up to 300° centigrade. If the silver disappears the freshly exposed copper surface is there to function.

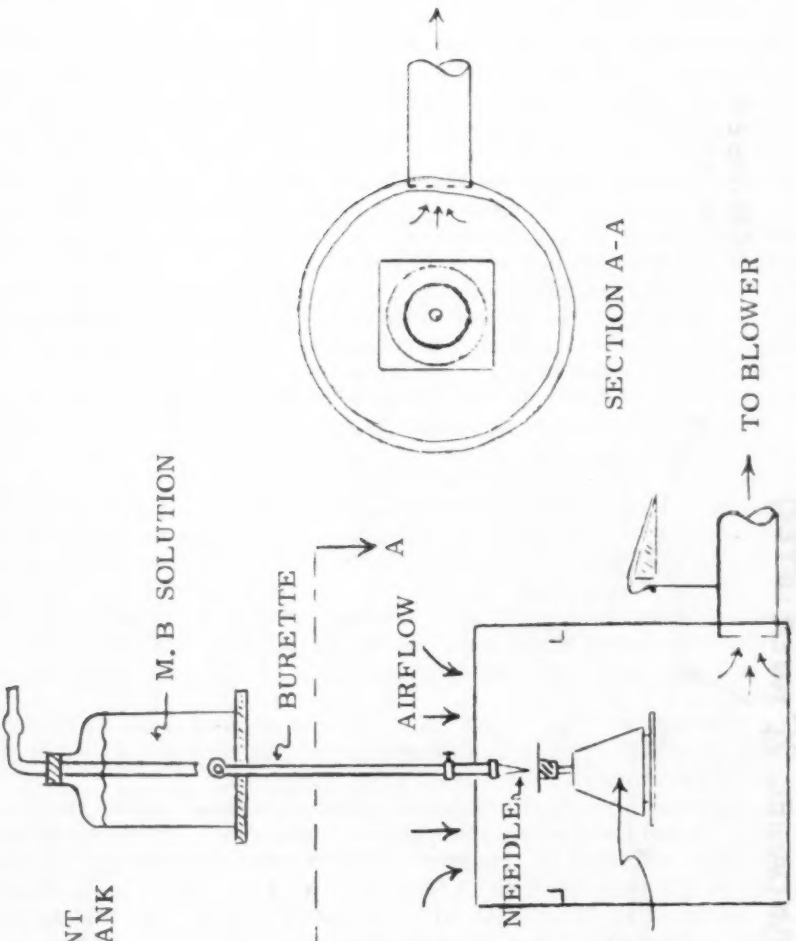


FIGURE 2.—Spinning disc aerosol generator.

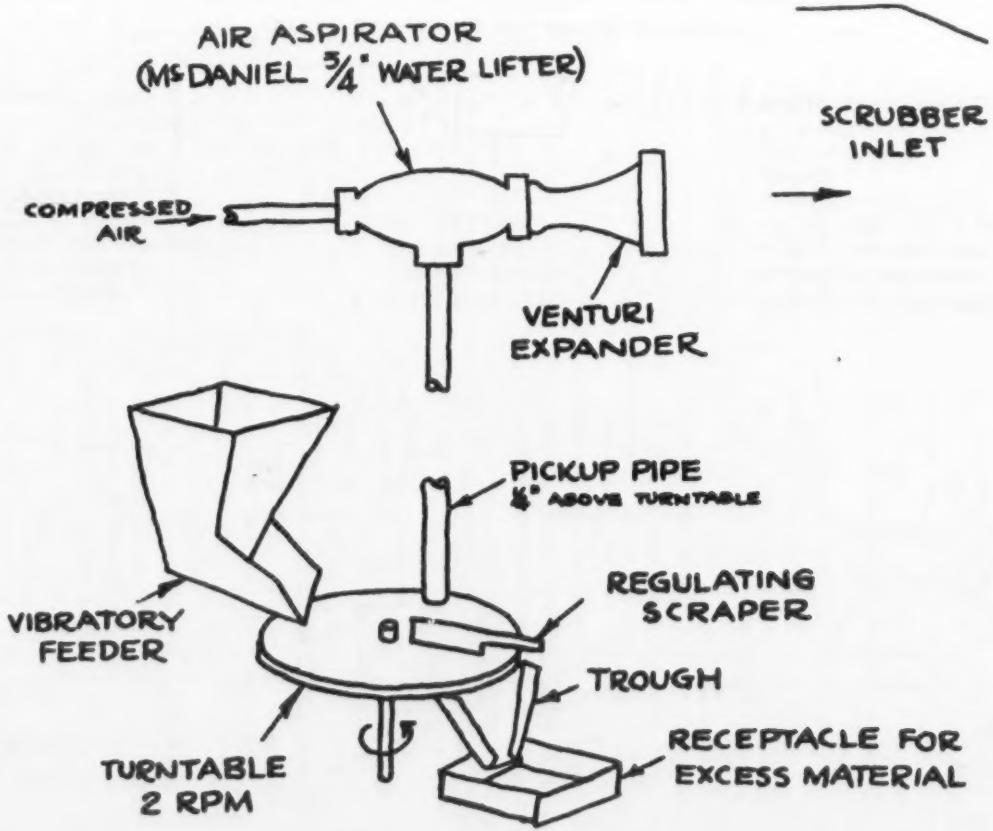
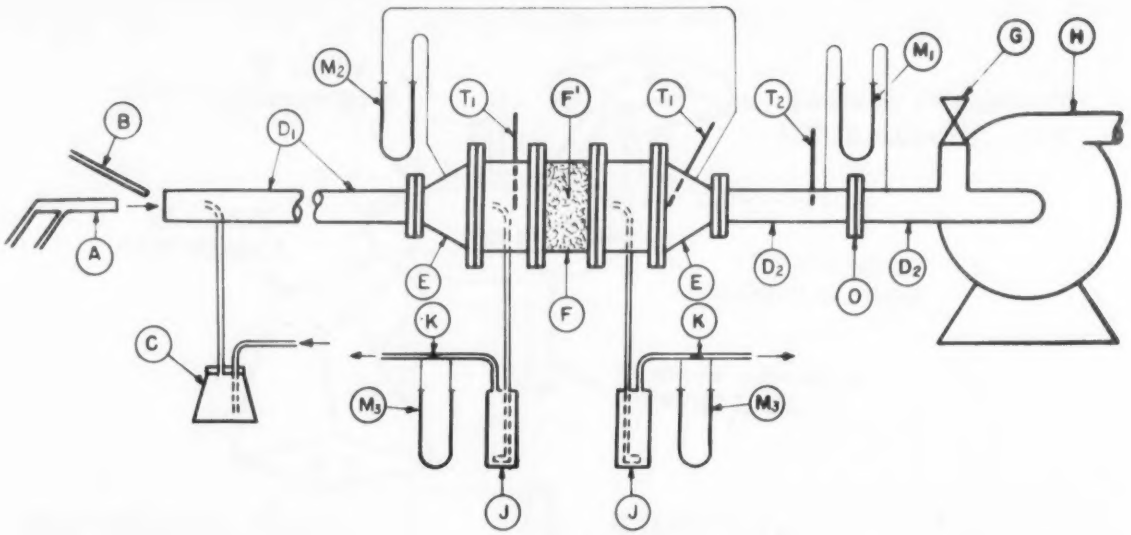


FIGURE 2A.—Dry dust generator.



A = GAS BURNER
B = STEAM SUPPLY
C = IODINE GAS GENERATOR
D_1 = 2" DIAM., 3'-4" LONG PIPE
D_2 = 2" DIAM. PIPES
E = 6" X 2" RED.
F = FILTER HOLDER, 6" DIAM., 2" DEEP
G = 2" VALVE, BY-PASS AIR FLOW CONTROL
H = EXHAUST FAN

F' = SILVER-PLATED COPPER RIBBON PACKING DENSITY 27 LBS./CU. FT.

J = FRITTED GAS ABSORBER
K = SAMPLE FLOWMETERS
M_1 = ORIFICE MANOMETER
M_2 = FILTER RESISTANCE MANOMETER
M_3 = SAMPLE MANOMETERS
O = ORIFICE
T_1 = THERMOCOUPLE
T_2 = THERMOMETER
← DIRECTION OF AIR FLOW

EXPERIMENTAL EQUIPMENT FOR IODINE COLLECTION STUDIES

FIGURE 3.—Experimental equipment for iodine collection.

It is important to emphasize that this simple device can be incorporated in existing systems without adding any appreciable fan or air mover load. There are other methods possible for iodine removal which we and others have also studied such as activated charcoal and carbons, but these impose a fire problem.

We believe the silver-plated copper provides iodine removal defense in depth. Not only does it provide the silver as a reaction surface, but if the silver fails or is removed the protected copper when exposed can fix more iodine. This development has now reached the stage where it is under active consideration for application on some large production and research piles. These simple iodine reductors can also provide suitable standby protection for use in containment vessels such as reactor housing or buildings. Here they can be used to decontaminate building air after an accident which causes fission product release.

On a similar type of problem which involves iodine as well as other fission gases we have at AEC request been acting as consultant to the portion of the Pluto project being undertaken by Curtiss-Wright. We have assisted them designing their study and setting up approaches for an aerosol cleaning train in which some of our developments at the Harvard Air Cleaning Laboratory are incorporated.

Another current problem on which we are now engaged in solving is the development of an inexpensive incineration device for solid waste (see fig. 4).

This is the incinerator which we are trying to develop. The problem is not the burning but the cleaning of the waste gases that come from the incinerator. The Bureau of Mines had a contract with AEC to develop an inexpensive incinerator. We found in trying to evaluate the air cleaner proposed for it that the tars produced in burning plugged the cleaning device so we could not get any air though it.

We have developed a refractory slag wool filter made from inexpensive byproduct blast furnace slag which will operate at filtration temperatures close to 1000° F. This filter (fig. 4A) will collect the effluent from the incinerator at values exceeding 99 percent without difficulty. The combustion work was originally done at the Bureau of Mines for the development of the incinerator portion of the unit, however, we have modified it significantly by reducing its size and successfully filtering the combustion gases.

A major item in AEC laboratory and contractor installations is the cost of air and gas cleaning. Like all waste disposal it poses a definite burden on capital as well as operating costs. The capital expenditures in some new facilities handling materials which may produce very active dusts and fumes may amount to as much as 25 percent of the initial cost. A new filter installation for plutonium fuel element fabrication calls for this magnitude of expenditure for the containment as well as filtering the effluent. In this connection, this year, we are undertaking an intensive economic survey of all major installations under major AEC contracts to determine capital outlay, maintenance in the form of frequency of changing, kind of replacement necessary, failures, all economic factors with regard to filters, and other types of cleaning devices. Naturally, we feel that

FIGURE 3.—Experimental equipment for iodine collection.

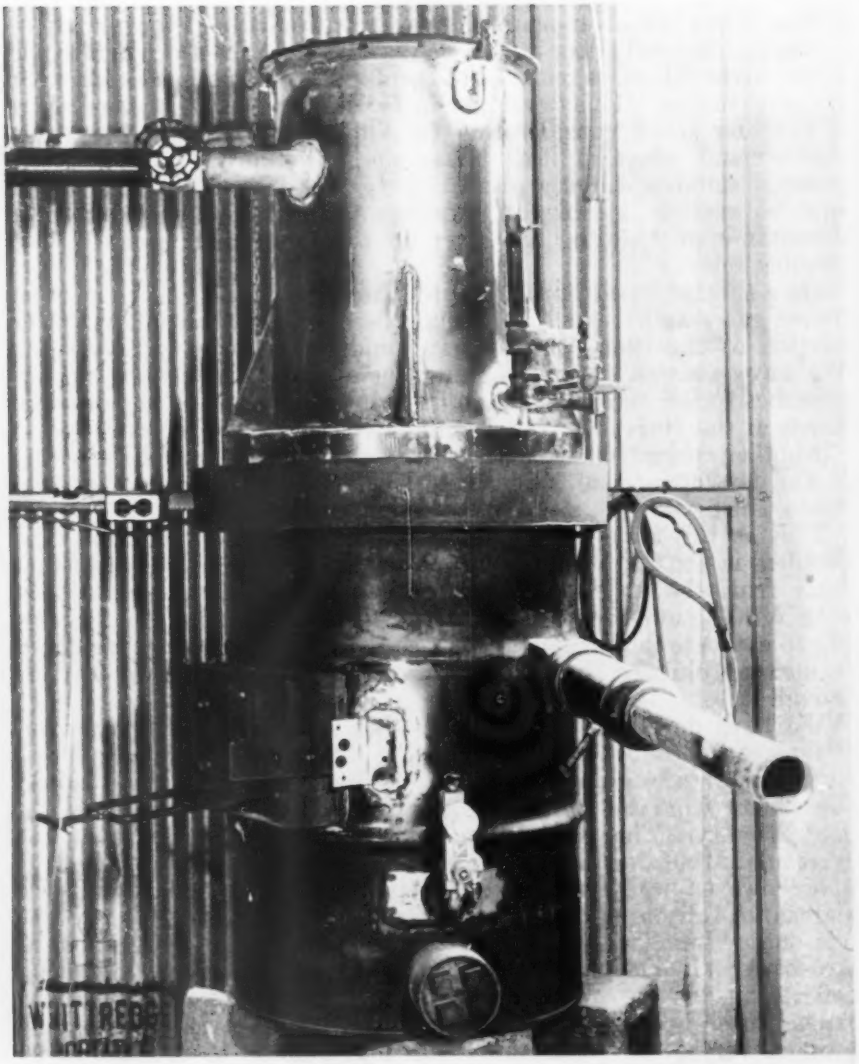


FIGURE 4.—Institutional type incinerator.

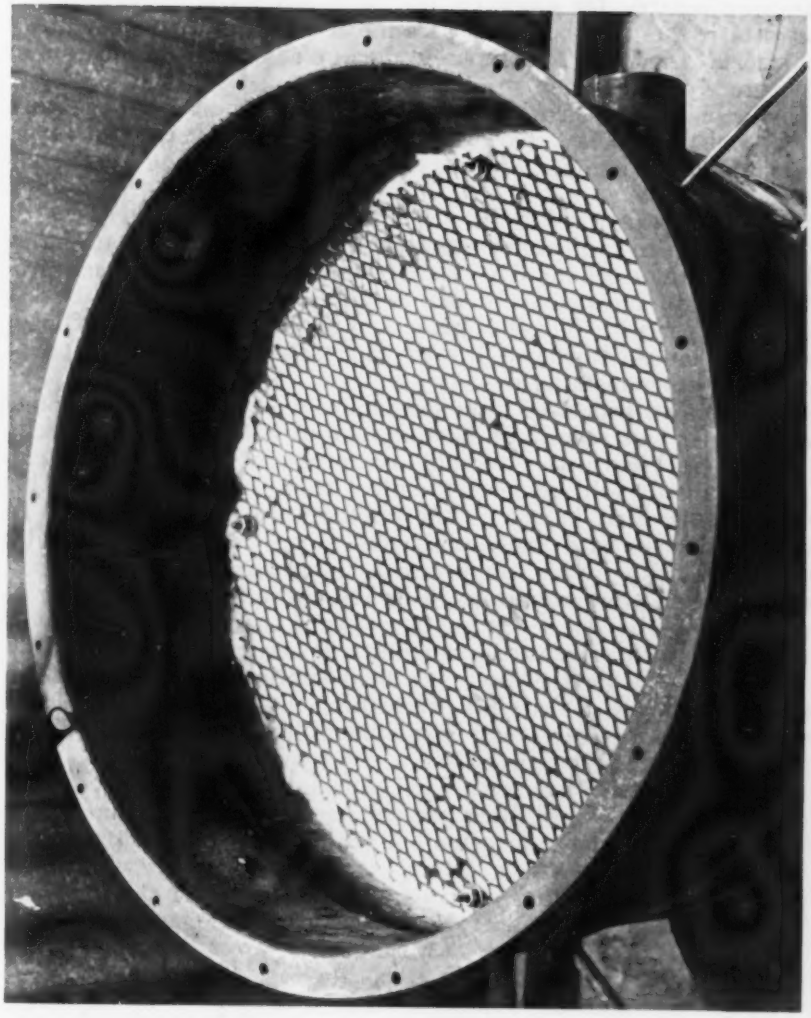


FIGURE 4A.—Filter unit for incinerator. Cover removed.

this is an important factor in deciding to what extent private industry will be encumbered in providing protection for the public as well as their own personnel.

We are also undertaking the development of new filtration devices which will operate at lower airflow resistance—energy consumption—and at high efficiency with lower capital costs.

This cuts down energy consumption and we hope to get higher efficiency with lower capital cost.

In this regard, for example, we have developed a very simple electrostatic fluidized bed filter as a means of cleaning supply air to laboratories (fig. 5). This filter produces a charge by fluidization of polystyrene granules.

This is one approach where we electrify a medium much the same way as you would get a charge sliding across a plastic car seat cover. We utilize the friction charge as a means of developing an electrostatic charge.

While it appears very useful for this purpose it is unlikely that it can be applied to radioactive effluents of high loadings, because they will leak off the mechanically created charge. It does, however, provide a way to inexpensively reduce atmospheric dust loadings as much as 99 percent. This has proved to be the major source of loading which causes shortened life of filters used in most AEC supported and other installations.

An important aspect of filter development is the need for remote handling. In this regard we have developed a simple fibrous media filter (fig. 6) known as a variable compression filter. Its life can be extended manyfold by density control from a distant point. This device is illustrated in one of the photographs on the plaque. In essence it consists of a resilient fibrous—phenolic bonded—fiberglas which is initially highly compressed. It is then allowed to relax gradually or in graduated steps as its resistance rises. The collected dust migrates from the center surface toward the outside as the filter is relaxed. Each relaxation provides a lowering of pressure drop and extended life for the filter. In field applications to date, it has been applied on small scale for precleaning in glove boxes and small operations within research and development laboratories. It could be applied to highly active materials where remote control is desirable thus giving extended life for a fixed initial cost. This cost does not exceed the ordinary fixed filter instalaltion by a large amount.

Lastly, I would like to mention our studies in regard to the effects of blast or shock waves on filters. A major problem with AEC facilities, as well as other contractor applications, is that of civil defense, particularly the effect of nearby weapon or gas explosions.

I might interject here the fact that after providing these well-protected AEC facilities all with elaborate air cleaning or any other type of user of radioactive materials and a weapon or an explosion goes off nearby this will cause airflow to reverse back through the filter.

Three years ago we explored the effect of such explosions in the laboratory and determined what would happen to shock wave exposed filters or other air cleaners. Some of these devices have operated for as much as 4 years without replacement and effectively removed 99.9 or more percent of contaminants. Our studies indicated

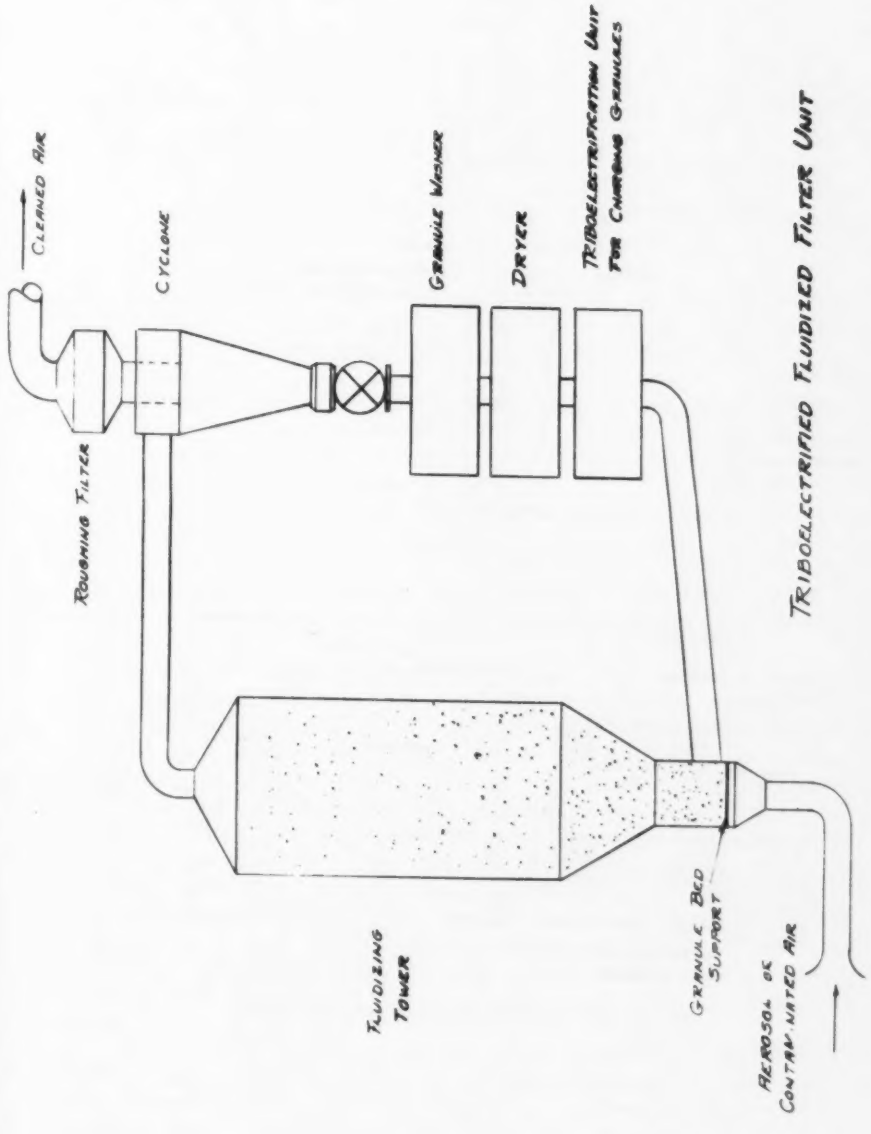


FIGURE 5.—Triboelectrified fluidized filter unit.

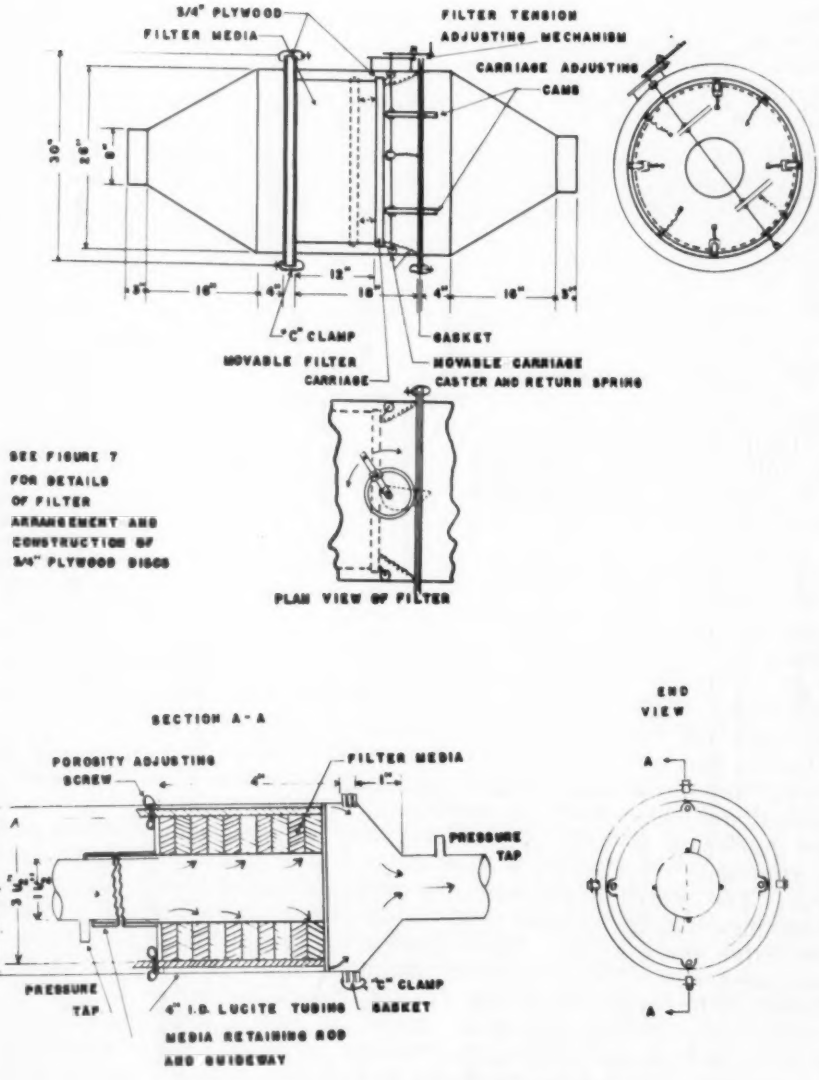


FIGURE 6.—Variable compression edge filter.

that if the filter did not fail from shock wave created by the blast from a nearby weapon detonation or explosion, the dust which was deposited would nearly all be released from the filter. This would then be disseminated through the ducts in the system to the laboratories and rooms. This effect is illustrated by the shock tube photographs. Extended laboratory studies showed that filters exposed to overpressure of 3 to 4 inches of mercury (below what might be encountered over 2½ miles from a weapon of Hiroshima tonnage) lost 90 percent or more of the deposited dust. We checked this phenomena in the field at two installations during Operation Plumbob in Nevada in September 1957. One simulated stack, duct, and filter installation was made comparable to a typical chemical plant and the other to a research facility installation. These two were at distances of 5,000 and 10,000 feet, respectively, from a weapon which was about one-half nominal yield. In this case field studies confirmed laboratory data. It was found that dust from loaded filters was removed at values comparable to the laboratory data.

The direct effect of this study was to indicate that these filters must be protected against external blasts by some attenuating device to dissipate the shock wave and prevent significant dispersion of the collected dust.

A beneficial aspect was that by using this technique of producing shock waves by paper diaphragm rupture we have been able to effectively clean deep slag filters developed for high-temperature fume collection for another purpose.

Figure 7A, 7B, and 7C shows the filters that were placed in the house at 10,000 feet from the weapon fired in Nevada. The dust dispersed on the floor which can be readily seen was originally placed on the filters. As a practical development which the British call serendipity—we are now getting some beneficial effects from this blast approach and finding out that it can clean filters effectively.

Future needs: In the field of gas cleaning for radioactive wastes several important aspects need continuing long-range studies. Economical methods for the collection and containment of radioactive rare gases such as Krypton 85 and Xenon 133 are necessary if we are to approach a nuclear power economy on a safe and inexpensive basis. The cost of removal of such gases at the present time calls for techniques which are only reasonable if very small volume or low flow rates are involved. In cleaning high-temperature gases contaminated with fine particulates it is necessary to provide filters which will function above 1,000° F. To date such filters are only experimental and need further development and study. They would be used for high-temperature reactors under development and, in the not too distant future, for test stands for nuclear rocket and ramjet engines.

The reduction of high- and medium-level and in some case low-level waste by evaporation or calcining produces aerosols which must be removed economically, as all waste processing must be done with low-operating costs. Methods of containing such particulates so they do not produce a secondary environmental contamination problem or a hazard to operators are necessary. This situation needs further research to develop much less expensive equipment and procedures than those now employed.

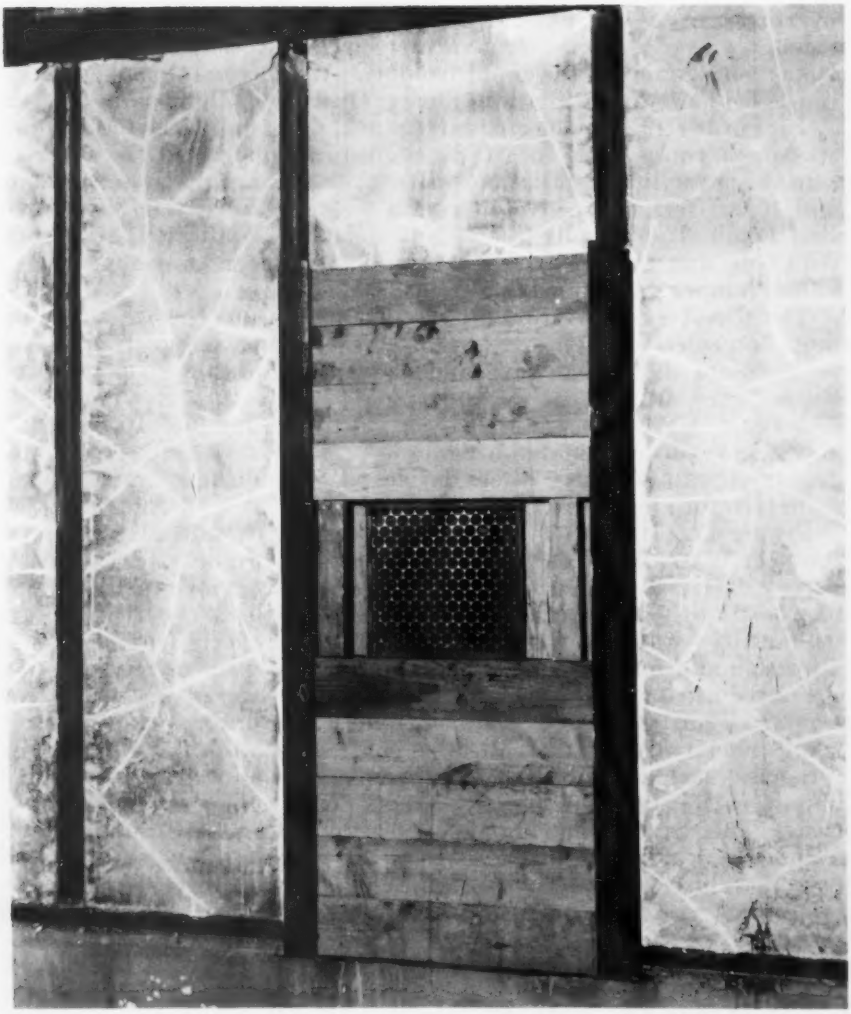


FIGURE 7A.—Preshot (above). Postshot (next page). Supply air glass fiber filter before and after >2 psi shock pressure.

FIGURE 7B.—Postshot. Dust blowoff from AEC filter, 0.7 p.s.i.

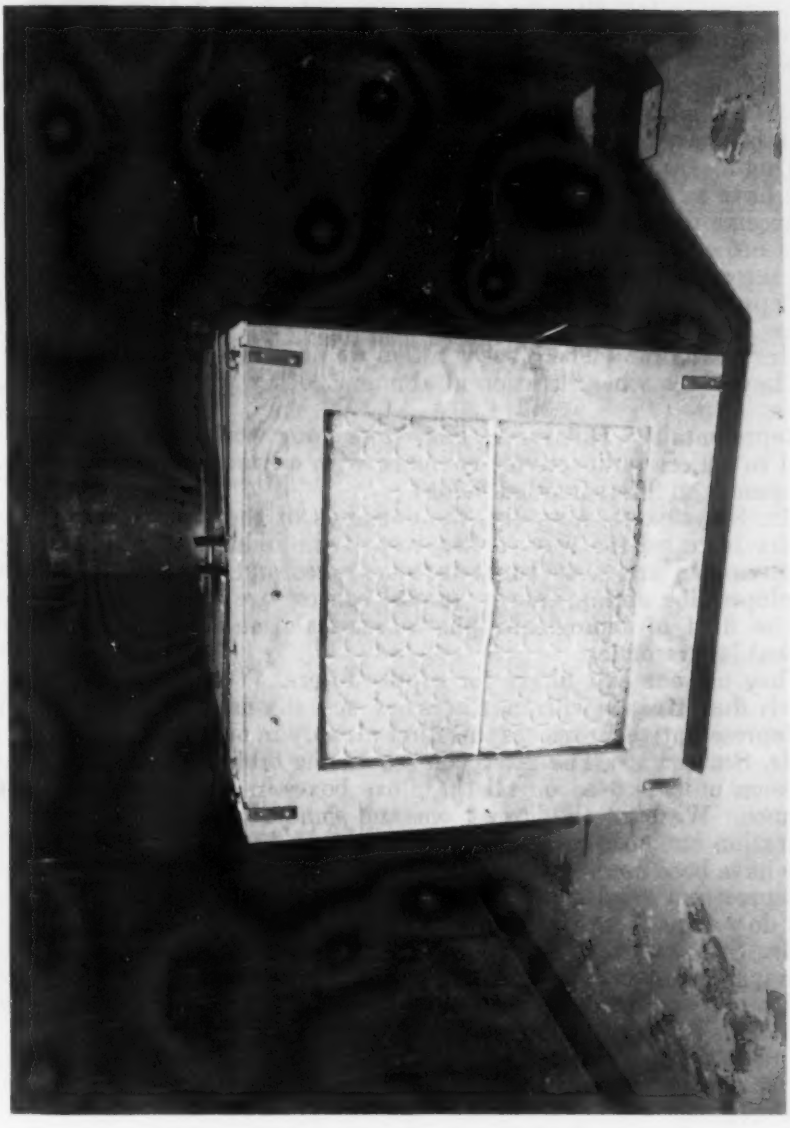


FIGURE 7C.—Postshot. Partial dust recovery by exhaust air filter, 0.7 p.s.i.

FIGURE 7B.—Postshot. Dust blowoff from AEC filter, 0.7 p.s.i.

Representative HOLIFIELD. Do you believe that we have a good opportunity of developing this type of handling of this high-level material?

Mr. SILVERMAN. I believe we have. I think the aerosol problem that is associated with trying to reduce the volume will involve high-level activity which I believe we can control.

Representative HOLIFIELD. Can you put it in a time period of experimentation?

Mr. SILVERMAN. I would say within the next 3 to 5 years. You see, one of the problems in cleaning high-level wastes and controlling high-level activity aerosols is the high radiation levels that the media will then have to withstand.

This means material studies and media. When you have a filter you have a large exposed area of material and this gives it a chance to receive damage on small fibers or fragments. There is a problem here not only associated with technology in our field, but technology in glass and other media that might be used for the filter construction.

Representative HOLIFIELD. What degree of Fahrenheit can your filters at this time stand?

Mr. SILVERMAN. The present filters we have can go up to 1,000° F. We have done some filtration at almost 2,000° F. on an experimental basis.

Representative HOLIFIELD. How does your work on filters in this field to collect radioactivity compare with advance research and development on filters in other fields?

Mr. SILVERMAN. Actually, the demands of the atomic energy industry have led the way for the rest of the industry. The cleaning requirements are 1,000 times in some cases and some of the filters developed for atomic energy aerosol control are now being applied in the field of biologicals, pharmaceuticals, and also in precision optical laboratories.

They use our exit filters for supply filters. You can make pretty nearly dust-free air with the filters now actually used.

Representative BATES. Is this filter already in operation?

Mr. SILVERMAN. The filter you see on the table, the variable compression unit, is used on all the glove boxes in one building in Los Alamos. We built the largest one and some of these are under consideration but no large-scale ones other than large numbers of small ones have been used.

Representatives BATES. After you come up with an idea like that, how do you get it into operation?

Mr. SILVERMAN. Well, we try to introduce our data at the air cleaning seminars. For example, the silver filter caught on like wildfire, I would say, because the pile effluent can be a problem. In some cases in hot cell processing they are also concerned.

This type of device is so simple, in fact, it almost looks too simple, that it can be placed in existing systems and give one more barrier of protection.

Since we have started this development for the ANP project, we have had more interest in people who have standby reactor control problems. The medical research reactor at Brookhaven wants to use this device as a standby emergency filter.

In case of accident, you close the building and then circulate the air through this unit because it has, as far as we know, infinite shelf life. If you took one of those plated units out and blew through it you would find its resistence to flow is quite low. Hence, it could go into existing systems and still not encumber the fan or blower capacity.

Representative HOLIFIELD. What is the theory?

Mr. SILVERMAN. The theory is quite simple. The silver or the copper forms the respective iodide which prevents the volatility of the iodine. Iodine being a fairly volatile compound and a strong oxidizing agent, reacts readily with copper or silver. But copper will take up oxygen in preference to iodine. That is why we silverplate it to provide a protective reactive surface.

Silver iodide is fairly stable up to 400 degrees Centigrade. Above this value it volatilizes and comes off as particles which the filter would catch. This silver reductor is therefore placed either before or after the filter depending on the temperature situation.

Representative HOLIFIELD. That is very interesting. If there are no further questions, thank you very much, Dr. Silverman. We will include your formal statement here, as well as some additional papers on this subject.

(The material referred to follows:)

AIR CLEANING STUDIES
(AEC Contract AT(30-1)-841)
HARVARD UNIVERSITY

Leslie Silverman, Sc.D.
Professor of Engineering in Environmental Hygiene
Director of Radiological Hygiene Program

Air and gas cleaning for nuclear energy processes differs from general cleaning problems in two major respects. One is the high order of toxicity of the contaminants, and in the second the cleaning device becomes dangerously contaminated and thus poses health problems due to radiation or disposal of collected materials. Radioactive gases and particulate matter in solid or liquid forms are the basic cleaning problems. Because of their high toxicity the degree of cleaning necessary is much severer than for most nonradioactive materials.

Air- and gas-cleaning problems arise from the mining, refining, and production of uranium and thorium. In providing cooling air for reactors or for shielding, contamination results from induced radioactivity in particulates conveyed by the cooling air if it is not well precleaned. Cooling air may also become contaminated with radioactive gases or particulates resulting from failure or from erosion of fuel elements.

Processing of reactor elements or slugs results in gaseous and particulate emanations from fission products, which create radioactive aerosols requiring nearly complete removal from the air stream before discharge to the atmosphere. Laboratory and pilot production of special isotopes and metals, recovery of certain materials, and isotope separation processes are operations which create radioactive contaminants.

Reduction of bulk volume of waste by incineration or evaporation of liquids each may create air-borne particulates which require special treatment. The air and gas cleaners by their recovery function provide solid- or liquid-contaminated materials which must be processed or handled. The contaminants range from rare gases, such as Argon (A^{41}), which are difficult to recover, to highly corrosive acid gases from metal extraction processes, such as hydrogen fluoride (HF). Solid and liquid particulates may be organic or inorganic and may range in size from less than 0.05μ to 20μ. The finest particulates arise from metallurgical fumes evolved by burning or vaporization, and the coarsest are acid-mist droplets.

The purpose of this presentation is to give the highlights of the general program on air and gas cleaning research and development which has been conducted at Harvard under AEC sponsorship through its Division of Reactor Development since February 1950. A two year preliminary study on fundamental information and approaches to air cleaning was undertaken for the New York Operations Office in 1948-50. The over-all project has thus been under active investigation for approximately ten years.

Scope and Functions

The scope and functions of the Harvard Air Cleaning Laboratory are in the fields of consultation, research and development. Our laboratory and field work can be best described under five main objectives:

1. Our major responsibility is to perform research and develop new procedures or modifications of existing approaches to solve nuclear energy gaseous waste problems. These are either brought to our attention by consultations with various site personnel or are conceived by us as approaches to basic problems associated with production, fixation and recovery processes.

2. We serve as a consulting as well as a correlating and collating agency to bring together information on air and gas cleaning problem approaches for the National Laboratory sites and other contractors. This information is then disseminated by means of field trip reports, seminars (discussed later under 5), or reference handbooks such as the Handbook on Air Cleaning.

3. There are many air and gas cleaning problems that develop in new nuclear energy applications. We are often requested to provide evaluation of equipment for an AEC application on an unbiased basis. The Atomic Energy Commission through its contractors prrchases a considerable amount (millions of dollars per year) of air and gas cleaning equipment, some of which may be new and untried, or have to be adapted to special purposes. For new or relatively untried devices we have upon AEC request only supplied test evaluations as to their merits. We do not consider this a primary function, but serve in this regard when asked to provide an unbiased opinion concerning equipment performance on aerosols or under conditions peculiar to AEC needs.

4. In relation to the above type of laboratory investigation it is necessary to follow such studies in the field, therefore, we are concerned with the development of suitable test methods and evaluation procedures for performance under many unusual conditions.

5. We provide upon request training and education for AEC or contractor personnel by assignment to our laboratory, by consultations and discussions with various contractor organizations and groups. In this connection we have held a number of information seminars both classified and unclassified. The sixth one is scheduled for this year.

These seminars are for interested AEC contractor personnel who have related problems in the air and gas cleaning field. The last seminar (5th) for the first time was opened to access permit holders. Typical examples of these seminar publications are shown by illustration. These seminars give us an opportunity to acquaint those in the field with new developments and to provide information and data on items pertinent to certain problems. A limited number of personnel from various sites also spend time at our laboratory to become familiar with new evaluation techniques and approaches.

Kinds of Problems Under Active Study

It is rather interesting to point out the basic changes in thinking in this field in the ten years since we have been involved in air and gas cleaning investigations for the AEC. In the early days, wet collectors were considered as optimum devices since they were capable of collecting the particulate matter, dust, fumes, etc. as an aqueous suspension which could then be readily piped to the liquid waste disposal plant for treatment and storage. The liquid waste problem has now reached "the point of no return" so to speak and it is now necessary to convert these stored liquids into solid wastes. This conversion means production of aerosols, fumes, and mists with their attendant air cleaning problems. Thus, the problem has never been really solved but merely by-passed temporarily. As you know, a certain amount of liquid storage will be necessary until other techniques become available. Wet collector performance actually has left much to be desired since corrosion, carry-out, inefficiency, plugging, and other problems encountered in practice has made it desirable in many instances to substitute dry collection.

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We believe the silver-plated copper provides defense in depth. Not only does it provide the silver as a reaction surface, but if the silver fails or is removed the protected copper when exposed can fix more iodine. This development has now reached the stage where it is under active consideration for application on some large production and research piles. These simple iodine reductors can also provide suitable standby protection for use in containment vessels such as reactor housing or buildings. Here they can be used to decontaminate building air after an accident which causes fission product release.

On a similar type of problem which involves iodine as well as other fission gases we have at AEC request been acting as consultant to the portion of the Pluto project being undertaken by Curtiss-Wright. We have assisted them designing their study and setting up approaches for an aerosol cleaning train in which some of our developments at the Harvard Laboratory are incorporated.

Another current problem which we are now engaged in solving is the development of a inexpensive incineration device for solid waste. Our primary concern in this project is that development of a suitable gas cleaning is one of the most important factors in preventing environmental contamination. Our experience has shown that it is difficult to burn the waste completely, thus tarry combustion products would plug the kinds of filters now in use. We have developed a refractory slag wool filter made from inexpensive by-product blast furnace slag which will operate at filtration temperatures close to 1100°F. This filter will collect the effluent from the incinerator at values exceeding 99% without difficulty. A model of this incinerator filter is shown in the accompanying drawings. The combustion work was originally done at the Bureau of Mines for the development of the incinerator portion of the unit, however, we have modified it significantly by reducing its size and successfully filtering the combustion gases.

A major item in AEC laboratory and contractor installations is the cost of air and gas cleaning. Like all waste disposal it poses a definite burden on capital as well as operating costs. The capital expenditures in some new facilities handling materials which may produce very active dusts and fumes may amount to as much as 25% of the initial cost. A new filter installation for plutonium fuel element fabrication calls for this magnitude of expenditure for the containment as well as filtering of the effluent. In this connection, this year, we are undertaking an intensive economic survey of all major installations under major AEC contracts to determine capital outlay, maintenance in the form of frequency of changing, kind of replacement necessary, failures, all economic factor with regard to filters and other types of cleaning devices. Naturally, we feel that this is an important factor in deciding to what extent private industry will be encumbered in providing protection for the public as well as their own personnel.

We are also undertaking the development of new filtration devices which will operate at lower air flow resistance (energy consumption) and at high efficiency and with lower capital costs. In this regard, for example, we have developed a very simple electrostatic fluidized bed filter as a means of cleaning supply air to laboratories. This filter produces a charge by fluidization of polystyrene granules. While it appears very useful for this purpose it is unlikely that it can be applied to radioactive effluents of high loadings, because they can leak off the mechanically created charge. It does, however, provide a way to inexpensively reduce atmospheric dust loadings as much as 99%. This has proved to be the major source of loading which causes shortened life of filters used in most AEC supported and other installations.

An important aspect of filter development is the need for remote handling. In this regard we have developed a simple fibrous media filter known as a variable compression filter. Its life can be extended manyfold by density control from a distant point. This is illustrated in one of the attached photographs. In essence it consists of a resilient fibrous (phenolic-bonded) fiberglas which is initially highly compressed. It is then allowed to relax gradually or in graduated steps as its resistance rises. The collected dust migrates from the center surface towards the outside as the filter is relaxed. Each relaxation provides a lowering of pressure drop and extended life for the filter. In field applications to date, it has been applied on small scale for pre-cleaning in glove boxes and small operations within research and development laboratories. It could be applied to highly active materials where remote control is desirable thus giving extended life for a fixed initial cost. This cost does not exceed the ordinary fixed filter installation by a large amount.

Lastly, I would like to mention our studies in regard to the effects of blast or shock waves on filters. A major problem with AEC facilities as well as other contractor applications is that of civil defense, particularly the effect of nearby weapon or gas explosions. Three years ago we explored the effect of such explosions in the laboratory and determined what would happen to shock wave exposed filters or other air cleaners. Some of these devices have operated for as much as 4 years without replacement and effectively removed 99.9+ or more percent of contaminants. Our studies indicated that if the filter did not fail from shock wave created by the blast from a

nearby weapon detonation or explosion, the dust which was deposited would nearly all be released from the filter. This could then be disseminated through the ducts in the system to the laboratories and rooms. This effect is illustrated by the shock tube photographs. Extended laboratory studies showed that filters exposed to over-pressure of 3 to 4 inches of mercury (below what might be encountered over 2½ miles from a weapon of Hiroshima tonnage) lost 90% or more of the deposited dust. We checked this phenomena in the field at two installations during operation Plumbob in Nevada in September, 1957. One simulated stack, duct and filter installation was made comparable to a typical chemical plant and the other to a research facility installation. These two were at distances of 5,000 and 10,000 feet respectively from a weapon which was about ½ nominal yield. In this case field studies confirmed laboratory data. It was found that dust from loaded filters was removed at values comparable to the laboratory data.

The direct effect of this study was to indicate that these filters must be protected against external blasts by some attenuating device to dissipate the shock wave and prevent significant dispersion of the collected dust.

A beneficial aspect was that by using this technique of producing shock waves by paper diaphragm rupture we have been able to effectively clean deep slag filters developed for high temperature fume collection for another purpose.

Future Needs

In the field of gas cleaning for radioactive wastes several important aspects need continuing long range studies. Economical methods for the collection and containment of radioactive rare gases such as Krypton 85 and Xenon 133 are necessary if we are to approach a nuclear power economy on a safe and inexpensive basis. The cost of removal of such gases at the present time calls for techniques which are only reasonable if very small volumes or low flow rates are involved. In cleaning high temperature gases contaminated with fine particulates it is necessary to provide filters which will function above 1,000°F. To date such filters are only experimental and need further development and study. They would be used for high temperature reactors under development and, in the not too distant future, for test stands for nuclear rocket and ram-jet engines.

The reduction of high and medium level and in some cases low level waste by evaporation or calcining produces aerosols which must be removed economically, as all waste processing must be done with low operating costs. Methods of containing such particulates so they do not produce a secondary environmental contamination problem or a hazard to operators are necessary. This situation needs further research to develop much less expensive equipment and procedures than those now employed.

TREATMENT OF RADIOACTIVE WASTE GASES

By

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The disposal of radioactive waste gases from the plant scale processes at the Hanford Atomic Products Operation presents a problem that is of considerable importance in the plant operation. This paper is concerned with the equipment which has been developed for the efficient removal of the two principal contaminants: 1) gaseous radioactive iodine; and 2) an aerosol composed of other fission products. The program has led to the development of the silver reactor for the removal of radioiodine and glass fiber filters for removing the particulate matter suspended in the gas streams.

FILTRATION OF RADIOACTIVE AEROSOLS

A brief summary of the specifications which were established as the development and design goals for the Hanford process air filters is presented in Table I. It is evident that the more common types of commercially available dust collectors fail to meet one or more of these specifications.

TABLE I

AIR FILTER SPECIFICATIONS

1. A collection efficiency of 99.99 per cent for sub-micron particles present in low concentrations.
2. A minimum initial flow resistance commensurate with the desired collection efficiency.
3. A minimum of maintenance in the continuous operation of the unit.
4. A life expectancy in terms of years.
5. Containment of the collected radioactive materials in a manner that will not cause a subsequent disposal problem.

An expedient solution to the problem of removing radioactive aerosols from the Hanford waste gases was a fixed-bed filter consisting of successively finer gradations of sand, placed in a large underground container, and suitably equipped with air distributors and duct work.[1] The characteristics of the units agree well with the specifications in Table I and the filters have performed in a highly satisfactory manner to the present time; one filter is

now in its eighth year of operation. The sand filters, however, are bulky and expensive, and their measured efficiency (in the order of 99.7 per cent) is not adequate for the more highly contaminated gas streams.

Subsequent study[2] established that filters, which would meet all of the design specifications, could be formulated through the use of glass fiber beds. The investigation of the filtration characteristics of glass fibers consisted of: 1) the correlation of collection efficiency under start-up conditions with the superficial velocity of the gas stream and the bed depth and packing density of various types of glass fibers; 2) the correlation of flow resistance under start-up conditions with the same variables; and 3) a study of the expected service life of glass fiber filters. Complete details of the experimental procedures and graphs of all the data obtained on the various types of glass fibers are presented in Reference No. 2.

Supplementary studies revealed that the radioactive particulate matter in the Hanford process-cell air was predominantly in the sub-micron range(experimental values of the geometric mean particle diameter varied from 0.2 to 0.7 micron) and that the dust loading of the effluent waste gases was in the order 0.2 to 0.4 grains per thousand cubic feet. It should be noted that the experimental results discussed in this paper are directly applicable only to systems wherein the size distribution and concentrations of the suspended particulate matter are comparable to these values. In cases where a significant difference in particle size distribution exists, for example, the collection efficiency of a given fibrous bed may be appreciably different.

COLLECTION EFFICIENCY CORRELATION

It was determined that the collection efficiency of a glass fiber bed can be mathematically expressed by the following relationship:

$$DF = -\log (1 - \alpha) = C L^{a} \rho_p^{b} V^{c} \qquad (1)$$

Where:

α = over-all collection efficiency
DF = decontamination factor
L = bed depth, inches
ρ_p = packing density, pounds per cubic foot
V = superficial velocity, feet per minute
C = proportionality constant
a,b,c = empirical exponents

To determine the exponents for each type of glass fiber, the change in the collection efficiency was measured in a series of test runs in which only one parameter was varied at a time. Thus, to obtain the velocity exponent, the same bed depth and packing density of a test unit were retained throughout a number of runs, so that the following correlation of efficiency and superficial velocity was in effect.

$$DF = -\log (1 - \alpha) = C' V^{c} \qquad (2)$$

and

$$\log DF = \log \left[-\log (1 - \alpha) \right] = c \log V + \log C' \qquad (3)$$

By plotting the data on a logarithmic graph of decontamination factor versus

velocity and measuring the slope of the line, the velocity exponent was obtained. A similar procedure was employed to determine the exponents for the other parameters.

A compilation of the collection efficiency data for the more promising glass fibers is presented in Table II. For each type of glass fiber the value obtained for the bed depth exponent was less than one, as would be anticipated with a heterogeneous aerosol.

The value for the packing density exponent varied from 0.9 to 1.1. It is believed that the true value of this exponent is 1.0, and that the recorded variance was due to the experimental precision.

Throughout the velocity range of 0-75 feet per minute, the collection efficiency of any one type of fiber decreased as the superficial velocity was increased, indicating that the predominant mechanisms of particle removal were flow-line interception and diffusion of the particles to the fibers with their subsequent adherence.

TABLE II

EFFICIENCY PARAMETERS FOR GLASS FIBERS

$$DF = C\, L^{a}\, \rho_p^{b}\, V^{c} \qquad \text{(See 1)}$$

Fiber Number	Fiber Diameter (microns)	C	a	b	c
AA	1.3	4.6	0.8	1.0	-0.2
B	2.5	----	----	----	-0.25
55	15	0.085	0.9	1.1	-0.4
115K	30	0.054	0.9	0.9	-0.4
450	115	-----	----	----	-0.5

FLOW RESISTANCE CORRELATION

The flow resistance of fibrous glass beds was likewise correlated with the same operating variables. The data for the fibers which were selected for detailed study are presented in Table III, wherein flow resistance, or Δp, is expressed in terms of inches of water.

TABLE III

FLOW RESISTANCE PARAMETERS FOR GLASS FIBERS

$$\Delta p = K\, L^{x}\, \rho_p^{y}\, V^{z} \qquad (4)$$

Fiber Number	Fiber Diameter (microns)	K	x	y	z
AA	1.3	0.082	1.0	1.5	1.0
B	2.5	-----	---	---	1.0
55	15	0.00043	1.0	1.6	1.0
115K	30	0.00020	1.0	1.5	1.0

The bed depth exponents, as would be anticipated, were one. The velocity exponents were each one, demonstrating that laminar flow exists throughout the flow range (5 to 100 feet per minute) which was studied. The value for the packing density exponent was determined to be 1.5.

COMPARATIVE LIFE EXPECTANCIES OF GLASS FILTERS

The proper design of a highly efficient fibrous glass filter involves not only an adequate knowledge of the characteristics previously outlined, but also sufficient information regarding the on-stream properties to insure a maximum life expectancy. To provide this information, a series of tests were performed wherein the useful filtration life of various fibrous beds was determined as a function of the quantity of aerosol passed to the unit. A synthetic, methylene blue smoke was used as the testing medium since the generated aerosol had a mean particle diameter comparable to that of the radioactive aerosol and since the dust loading could be made sufficiently high to restrict the test period to a practical time interval.

In general, the test results showed that the use of forefilters having a larger fiber diameter or a lower packing density increased the filter service life. By the appropriate selection of individual glass fiber beds, a composite filter can be designed which will have a life comparable to that of a sand filter. It should also be noted that the glass fiber filter will provide a higher collection efficiency, a lower flow resistance, and a considerable savings in construction cost as compared to a sand filter.

CHEMICAL STABILITY OF GLASS FIBERS

One additional factor must be considered in the formulation of glass fiber filters; this is the chemical stability of the fibers. The large increase in surface area brought about by the formation of small fiber filaments results in a corresponding increase in its reactivity with acid, alkali, or water. The chemical stability is, therefore, a function of the glass composition and the chemical environment. It is advisable to consult the manufacturer concerning the suitability of a particular type of glass prior to its use in an installation.

THE DESIGN OF GLASS FIBER FILTERS

The data correlations can be used to design filters which will meet specific operating characteristics. Approximately 35 fixed-bed, glass fiber filters have been placed in operation at Hanford during the past eight years. The specific service conditions have involved flow rates ranging from 15 to 125,000 cubic feet per minute, different efficiency requirements, and different chemical environments. The best method of illustrating how the data can be handled to meet particular conditions is to consider two filter applications having rather widely different requirements.

Vessel Vent Filter

The first is a filter which was required for the decontamination of the vent gases from a process vessel. The air flow was approximately 250 cubic feet

per minute; a filtration efficiency in the order of 99.99 per cent was required; and, since the unit was to be installed in a process cell, it was important that the over-all height be kept to a minimum. A schematic diagram of the filter which was designed for this application is presented in Figure I.

The over-all height of the bed was kept to slightly over 42 inches through the use of individual filter layers having carefully controlled packing densities. The individual packing densities were accomplished by using supporting and confining screens. The predicted efficiency and flow resistance of this unit were 99.99 per cent and 4 inches of water, respectively.

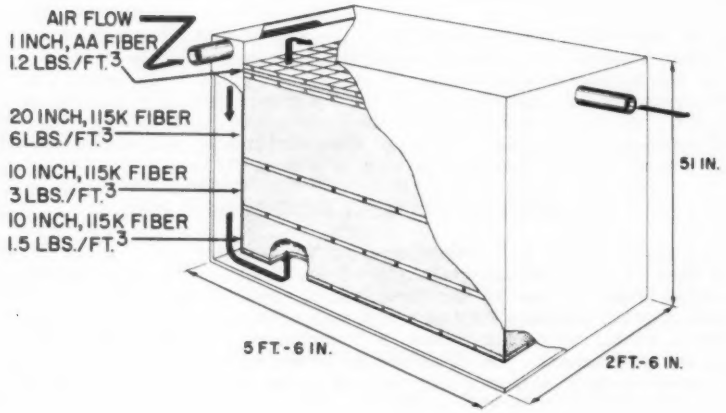

FIGURE 1
VESSEL VENT FILTER

This filter was later evaluated under actual service conditions. Aliquots of the upstream and downstream gases were passed through high efficiency monitoring filters. In this efficiency range, with only approximately one part in ten thousand passing the filter, and with the monitoring technique which was used, it is difficult to obtain definitive efficiency values. The data clearly established, however, that the efficiency of the glass fiber bed was greater than 99.9 per cent and probably near 99.99 per cent.

Ventilation Air Filter

A rather different application is that of a filter for the decontamination of the effluent ventilation air from a processing plant. In this instance, the air flow was 125,000 cubic feet per minute and the desired collection efficiency was 99.9 per cent. For filters of this large a size, the use of screens to maintain individual packing densities becomes impractical and certainly very expensive. The large ventilation air filters, however, are installed underground and fortunately, the increased cost associated with a deeper excavation is not very great. The ability to use a deeper filter bed also makes it possible to take advantage of another fact which is revealed by the basic data. As has been stated previously, the packing density exponent was determined to be 1.0 in the efficiency studies and 1.5 in the pressure drop studies. Consequently, a freely packed bed of bulk fibers can be designed to provide a given forefilter efficiency at a lower pressure drop than that of a filter having graded layers at constant packing densities. This will, of course, result in lower operating costs.

A schematic diagram of the filter which was designed for this application is presented in Figure 2. The filter is composed of two parts, a forefilter and a "clean-up" or high efficiency section. The purpose of the forefilter is to provide an adequate useful life for the unit. It consists of an 84 inch depth of freely packed, 115K Fiberglas with the filtration area sized for a superficial velocity of 50 feet per minute. The as-produced density of the 115K Fiberglas is approximately 1.5 pounds per cubic foot. There are screens at only the bottom and top of the forefilter and the weight of the glass fibers was used to obtain a packing density gradient from 1.5 pounds per cubic foot at the top to approximately 3.3 pounds per cubic foot at the bottom of the bed.

The high efficiency section consists of 0.5 inches of B Fiberglas at a density of 1.4 pounds per cubic foot and 0.5 inches of AA Fiberglas at 1.2 pounds per cubic foot. The combined one inch depth of the clean-up section is contained in commercial "V" type filter assemblies to provide a developed filtration area.

The air flow is downward through the forefilter (from lighter to greater packing densities) and then through the high efficiency section. The predicted collection efficiency and pressure drop values were 99.9 per cent and 4 inches of water, respectively.

The collection efficiency of this filter was also evaluated during actual service conditions and a more refined monitoring method was used. This was done by passing an upstream sample through a five stage cascade impactor and a downstream sample through a three stage cascade impactor; each impactor was followed with a AA Millepore filter. The efficiency based upon the total radioactivity in the samples varied from 99.76 to 99.98 per cent. The efficiency based upon a numerical count of the radioactive particles was 99.84 per cent.

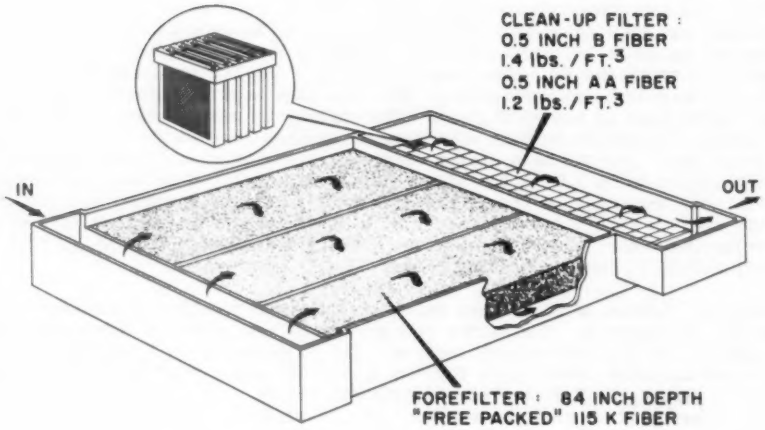

FIGURE 2
VENTILATION AIR FILTER

GENERAL OPERATING PERFORMANCE

The operating experience with glass fiber filters has been highly satisfactory. Experience has shown that two precautions are advisable: 1) care must be exercised in the assembling of the filters to insure that there will be no by-passing of the gas stream around the edges of the fine diameter, high efficiency sections; and 2) repeated soaking and drying of the AA Fiberglas should be avoided since this can lead to a rearrangement of the fibers and a lowered collection efficiency.

REMOVAL OF GASEOUS RADIOIODINE BY SILVER REACTORS

The specifications which were established as the development and design goals for the removal of gaseous radioiodine were essentially the same as those which have been described for the high efficiency filters. Preliminary studies were made of several methods of iodine removal and the silver reactor was selected as the process which best met all of the requirements. The basis of operation

is the use of a silver bearing, reacting bed at an elevated temperature. The iodine reacts chemically and is retained within the bed. A schematic diagram of a silver reactor assembly is presented in Figure 3.

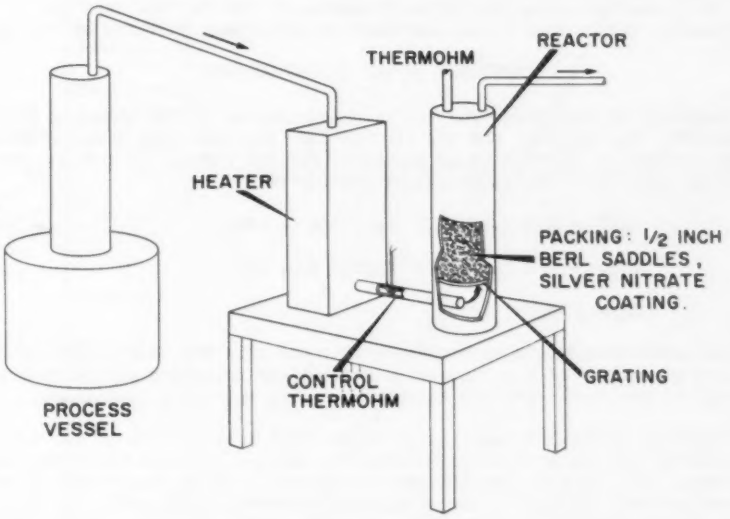

FIGURE 3
SILVER REACTOR ASSEMBLY

The process vent gases are heated to obtain the desired temperature. Electric heaters, steam heaters, and a series arrangement of a steam heater operating at constant load with an electric heater providing the fine temperature adjustment have all been used. The best operational control has been obtained with the latter method. The heating requirement is determined by measuring the temperature of the gas stream between the heater and the reactor tower. This temperature is used to provide a control signal to the heater units.

The silver reactor consists of a tower which can be packed with any suitable silver-bearing bed. The diameter of the tower should be sized to give a superficial velocity of approximately one foot per second. Where the space is available, a length to diameter ratio of approximately 4 is suggested; high collection efficiencies can be obtained with a considerably smaller length-diameter ratio but the useful life of the unit will be shortened.

The most economical means of obtaining a highly developed silver surface area for the reacting bed is through the use of Berl saddles which have been coated with silver nitrate, and this method has been the most widely used. For the preparation of this type of packing, unglazed ceramic Berl saddles are immersed in an 18-20 molal silver nitrate solution for one minute, allowed to drain, and then baked at 220 F for four hours. After baking, the packing is cooled to room temperature and then charged into the reactor tower. The control temperature for a reactor using this type of packing is 380 F. The reaction temperature will be more fully discussed in subsequent sections of this paper.

CHEMISTRY OF THE SILVER REACTOR

The chemistry of the silver reactor is quite complex.[3] The entering gases can contain NO_2, O_2, H_2O, N_2, and $ICl + I_2$ (or $ICl + Cl_2$ with some NOCl depending on whether iodine or chlorine is in excess). For the removal of iodine, the following individual reactions can be considered:

$$AgNO_3 + 1/2\ I_2 \rightleftharpoons AgI + 1/2\ O_2 + NO_2 \qquad (5)$$

$$AgNO_3 + 1/2\ I_2 + O_2 \rightleftharpoons AgIO_3 + NO_2, \text{ and} \qquad (6)$$

$$AgIO_3 \rightleftharpoons AgI + 3/2\ O_2 \qquad (7)$$

Thermodynamic considerations would predict, and this has been confirmed by a subsequent analysis of a portion of a reactor bed following its service life, that AgI is the stable product under the reactor operating conditions.

The situation is further complicated by the fact that in some of the reactor applications the gas stream can contain NH_3 and H_2 (at these times the oxides of nitrogen and probably the halogens are absent). Under these conditions, NH_3 combines with $AgNO_3$ to form an addition compound, $AgNO_3.xNH_3$ which in turn decomposes partially to yield $AgNO_3$, Ag metal, $AgNO_3.xNH_3$ and a trace of AgN_3. The thermodynamics of iodine removal by this method has been rather thoroughly considered.[3] Two of the more important factors should be emphasized. The equilibrium pressure of iodine increases with the square of the NO_2 pressure and to a lesser extent with the O_2 pressure as shown by the relationship:

$$P_{I_2} = \frac{(P_{NO_2})^2\ (P_{O_2})}{K^2} \qquad (8)$$

The equilibrium pressure of iodine is strongly dependent upon the reaction temperature. This is illustrated in Figure 4, which presents a plot of the calculated iodine pressure as a function of temperature. It can be readily seen that very high collection efficiencies are favored by a high operating temperature. With the use of a silver nitrate coating, however, the control temperature is limited to approximately 380 F. This is necessary since care must be exercised not to exceed the melting point of the silver nitrate and thus cause a flowing of the coating from the packing surface.

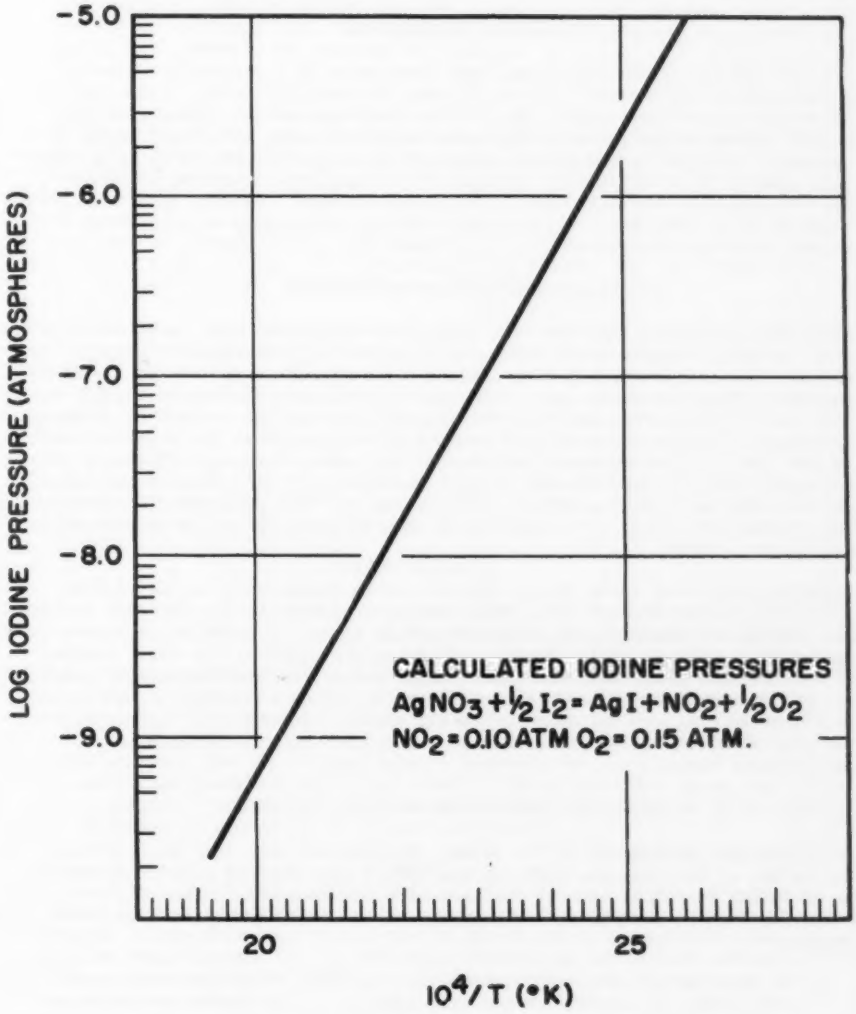

FIGURE 4
IODINE PRESSURE VS. TEMPERATURE

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It should be noted that higher collection efficiencies have been obtained in practice than would be predicted from the theoretical relationships which have been described. Although this shows that the calculations err on the pessimistic side, the basic validity remains as to the dependence of iodine removal upon temperature, NO_2 concentration, and to a lesser extent O_2 concentration.

COLLECTION EFFICIENCY

The optimum performance which has been obtained with a plant-scale reactor using a silver nitrate coated packing is a removal efficiency in the order of 99.99 per cent. Monitoring data indicate that the reactor operated in this manner for approximately one year before the collection efficiency began to decrease. It must be emphasized, however, that this represents optimum rather than general performance. As a result of the many variables which can affect the process, the over-all removal efficiency of "new" reactors has been in the range of 99.7 to 99.9 per cent and the over-all efficiency of "regenerated" reactors has been in the order of 99.5 per cent.

REGENERATION OF SILVER REACTORS

Experience has shown that when the collection efficiency of a reactor begins to fall it can be "regenerated" and a large measure of its removal efficiency restored. This is accomplished by fitting a spray head at the top of the reactor packing. The unit is allowed to cool to 150 F and the packing is sprayed with 0.04 cubic feet of five molal silver nitrate solution per cubic foot of ceramic packing. After the spraying, the reactor bed is heated to 220 F and allowed to bake for four hours; again the reactor is cooled, sprayed in the same manner, and then baked at 230 F for six hours. Following the two spraying and baking periods, the unit is returned to service. As has been previously mentioned, the removal efficiency of a regenerated unit is somewhat less than that of a new silver reactor.

Experience has also shown that a reactor can be regenerated in this manner some seven to ten times. After this number of regenerations, the flow resistance across the unit becomes excessive. This increased flow resistance is caused by a plugging of the bottom packing support grid with a heavy coating of silver nitrate crystals and other silver salts.[4] This deposit grows in size with succeeding regenerations because the liquid reaching the bottom grid is saturated and does not dissolve in any previous deposit. After seven to ten regenerations, the crystal mass on the supporting grid becomes almost continuous.

OPERATING PERFORMANCE OF SILVER REACTORS

The operating performance of the silver reactors has been very satisfactory. The nature of the process, however, requires a considerably greater attention to operating variables than is the case with the deep-bed fibrous filters. The following factors are particularly important in the operation of the silver reactors:

1. If the reactors are permitted to operate below 375 F, the collection efficiency is lowered; if the temperature falls below the condensation

point of nitric acid vapors (230 F), practically no iodine removal occurs. If a reactor using silver nitrate is permitted to operate above 413 F, the life of the unit will be seriously affected due to the melting and flowing of the silver nitrate coating from the column packing.

2. Either stable iodine or chlorine can saturate a reactor or displace radioactive iodine which has been collected. For this reason, care should be exercised that the chemicals used in the process do not contain appreciable amounts of chlorine or iodine.

There has been one instance of a fast exothermic reaction in a silver reactor. This followed an attempt to unplug a silver reactor which had been regenerated approximately ten times. An ammonium hydroxide flush was used to unplug the reactor. The flush was effective in decreasing the flow resistance of the unit. The reactor was then given a thorough water flush, dried, sprayed with silver nitrate solution, and returned to service. Shortly thereafter, a rapid exothermic reaction occurred. Laboratory information has shown that this reaction resulted from the decomposition of an unstable product which had been formed by a reaction with ammonia. The particular compound has not been identified; nor has the source of the ammonia been established conclusively.

Although the many years of uneventful, normal operation of the silver reactors would indicate that the reaction with ammonia occurred as a result of the NH_4OH flush, it cannot at this time, be stated with complete certainty that NH_3 in the gas stream could not react to form an unstable ammonium compound. As a result of this incident, ammonium hydroxide has been prohibited as a flushing solution and serious consideration is being given to either removing the NH_3 by scrubbing or to by-passing the gas streams which contain NH_3 around the silver reactor units. There is very little iodine associated with the gas streams which contain NH_3 but for simplicity in piping, these gas streams have been passed through the silver reactors.

FUTURE PROGRAM

A program involving both laboratory and prototype studies is being conducted to develop optimum procedures for the regeneration and flushing of the reactors.

The basic data establish that ultra-high collection efficiencies are favored by the use of higher reacting temperatures than are possible with the use of silver nitrate. Iodine removal at higher temperatures will be investigated with prototype equipment which will use a reacting bed consisting of dispersed elemental silver. The use of this type of reacting bed at a higher temperature has an additional potential advantage of simplifying operation since the present stringent requirements upon temperature control limits could be relaxed with less danger of impairing collection efficiency.

SUMMARY

Fixed-bed, glass fiber filters and the silver reactor have been developed and adopted at the Hanford Atomic Products Operation as the methods best meeting the requirements for the efficient removal of radioactive aerosols and gaseous radioiodine. A number of plant-scale filters and silver reactors have been installed and operated during the past eight years. The over-all operating performance of both types of equipment has been highly

satisfactory. The operation of the filters has been essentially maintenance-free and has been particularly uneventful. The more complex mechanism of the silver reactor requires a considerably closer attention to the operating variables in order to achieve optimum performance. Further improvements in the collection efficiency and ease of operation of the silver reactors appear possible and studies are in progress to define these conditions.

REFERENCES

1. Nucleonics, Waste Disposal Symposium, vol. 4, No. 3, p. 11 (1949)

2. Blasewitz, A. G., Carlisle, R. V., Judson, B. F., Katzer, M. F., Kurtz, E. F., Schmidt, W. C., and Weidenbaum, B., Filtration of Radioactive Aerosols By Glass Fibers, General Electric Company, Hanford Atomic Products Operation, Document No. HW-20847, Parts I and II, (4-16-51)

3. L. L. Burger, Thermodynamics of Iodine Removal With The Silver Reactor, General Electric Company, Hanford Atomic Products Operation, Document No. HW-38311 (July 1, 1955)

4. L. C. Amos, Regeneration of Silver Reactors, General Electric Company, Hanford Atomic Products Operation, Document No. HW-41053 (12-27-55)

SUMMARY OF RESEARCH AND DEVELOPMENT WORK CONDUCTED FOR THE U. S. ATOMIC ENERGY COMMISSION

Department of Sanitary Engineering
and Water Resources
The Johns Hopkins University
Baltimore 18, Maryland

February, 1959

Research and Development

The research and development work conducted by the Department of Sanitary Engineering and Water Resources of The Johns Hopkins University can be classified in five groups:

I. The investigation of surface contamination by radioisotopes, particularly those surfaces exposed to radioisotopes in waste drain connections and institutional incinerators. This was extended to a study of contamination and decontamination of clothing with an investigation of treatment methods for rendering harmless the resulting laundry wastes.

II. The investigation of disposal practices of the Atomic Energy Installations. This included a survey of ocean disposal practices, land burial practices and a cost survey of all waste disposal practices. A study of the pollution effects of the waste disposal practices of the uranium ore processing industry is currently being conducted.

III. The organization of conferences, at which scientists from disciplines that will be involved in the future development of waste disposal practices would be informed of the problems involved in the disposal of radioactive wastes. Working groups were briefed by the waste disposal men of A. E. C. and the study group of J. H. U.

Problems projected by the waste engineers were discussed by the conferees in the light of their various disciplines, and the research required to explore various ideas for disposal were outlined.

IV. The development of methods for the fixation of radio-isotopes on or in solid media. This has included work on adsorption on organic materials, the fixation of radio-nuclides on solid matrices, with accompanying studies of the separation of specific nuclides to make the fixation feasible.

V. The engineering study of problems facing the Atomic Energy Commission. A preliminary feasibility study for a land burial site in the Northeastern United States was conducted. At present a study of the problems of transportation of radioactive waste materials employing the newly developed Operations Research techniques is being conducted.

Group I. Item 1.

Radioactive Contamination and Decontamination of Rubber Gloves

The use of rubber gloves to avoid contamination of the hands when working with radioactive substances has been an established practice. These gloves are often regarded as expendable and discarded if they become contaminated. However, in large scale operations this becomes a rather costly procedure. In view of this, a laboratory investigation was undertaken at The Johns Hopkins University to study the extent to which rubber gloves are contaminated under various conditions by several different isotopes, and to find out how effectively they can be decontaminated, by simple procedures, to permit their reuse.

Samples of natural and synthetic rubber gloves exposed to solutions of P^{32}, I^{131}, and Sr^{89} were contaminated in varying degree by the different isotopes. Rate and extent of contamination were affected by duration of exposure, pH of solution, temperature of solution, roughness of surface, and concentration of isotope present, indicating preferential adsorption of the isotopes by the rubber.

Rate of uptake of P^{32} and Sr^{89} from isotopically dilute solutions exceeded that of carrier-free I^{131}. However, I^{131} proved to be the most difficult to remove from contaminated samples

Surgeon's gloves, supposedly of purest natural rubber, and the yellow latex gloves were found to be less susceptible than the neoprene and canner's gloves to contamination by P^{32}. Only minor differences were observed with the I^{131} and Sr^{89}. With regard to decontamination, surgeon's gloves proved superior in practically all tests.

An ordinary anionic detergent and regular Versene were consistently the most effective of the decontaminating agents tried. Agitation of the samples for 15 minute periods in the solutions was considerably more effective than simple immersion, and in most cases almost as effective as scrubbing. It seems doubtful that actual instances of glove contamination would ordinarily be quite as severe as encountered here, since relatively long periods of exposure to active solutions were used. Therefore, it would appear that ordinary laundering procedures, with perhaps the addition of Versene, should be able to adequately decontaminate rubber gloves, and thus prolong their useful life to some extent at least. Proper temperature and strength of detergent solution to be used in laundering would have to be determined to avoid deterioration of the gloves. Where only a limited number of gloves are involved, scrubbing of the individual gloves should give the best results possible.

A complete presentation of the study is given in the A.E.C. publication NYO-4519, "Contamination and Decontamination of Rubber Gloves."

Group I. Item 2.

Contamination of Metal Surfaces by I^{131} in Solution

The object of this series of studies at The Johns Hopkins University was to gain some insight into the principal mechanisms and factors involved in the contamination of drain systems by radioisotope wastes and to evaluate the hazards involved.

This particular investigation was concerned with the contamination of non-porous materials, chiefly the common metals and alloys used in the various components of a drain system, by radio-iodine (I^{131}) in solution. I^{131} has a fairly short half-life, but it is of prime importance since it is used in relatively large quantities, particularly by hospitals. The variety of conditions met with in the everyday use and disposal of the isotope are simulated by experiment.

It is evident from the experimental studies that some of the materials ordinarily used in drain systems can be contaminated by I^{131}-bearing wastes. With non-porous materials, chemisorption is chiefly responsible for high-level uptake of the I^{131}. Two conditions appear to be requisite for this contamination to reach potentially hazardous proportions:

(1) Ability of the substance to react chemically with the I^{131}.

(2) Relative insolubility of the reaction products.

Thus, the easiest way to minimize the possibility of excessive contamination is to use materials which do not meet conditions (1) and (2). Smooth, non-porous, more or less inert materials such

as glazed ceramics, baked enamel finishes, and certain plastic coatings should be most resistant to contamination. Black iron, duriron, galvanized iron, and stainless steel are among the safer materials to use in drains through which I^{131} will pass. Lead and the copper-bearing alloys should be avoided if possible.

If contaminable substances are used, it has been shown that hazards of some significance may be created. While they are generally not of alarming proportions, some attention should be paid to limiting the extent of contamination by control of one or more of the following factors:

(a) Concentration of I^{131} in the waste

(b) Time of contact between material and I^{131}

(c) pH of the waste.

Strong wastes could be diluted up before disposal to the sewer, and a reasonable quantity of water, say a total of several gallons, could be flushed down just before, during, and following the disposal. The rapid flow would cut the time of contact to a minimum, and chances for retention of highly concentrated waste liquid in traps or fittings would be reduced to a minimum. If the activity is of the order of several millicuries or more, further precautions could be taken, such as greater dilution with water, making the waste highly alkaline, or flushing down a strong detergent or drain cleaner following the disposal. Above all, extreme care should be taken in pouring the waste into the drain opening to avoid splashing and contamination of the exposed surfaces. These simple procedures would appear to be entirely adequate for the majority

of radioiodine users, without recourse to isotopic dilution or expensive decontaminant rinses. If the waste, however, is not entering a larger sewerage system with subsequent high dilution, or is being emptied directly into a body of water, isotopic dilution may well be justified as a precautionary measure against later concentration by living organisms.

Experience with P^{32} as phosphate solution indicates that considerable differences in behavior exist among the various radioisotopes with respect to contamination. Since conditions ideal for the disposal of one may actually promote contamination by another, the above recommendations for I^{131} must not be assumed to be applicable a priori to any other isotope.

A complete presentation of the study is given in A.E.C. publication, NYO-1573, "Contamination of Metal Surfaces by I^{131} in Solution."

Group I. Item 3.

Contamination of Plumbing by Low-Level Radioisotope Wastes

The previous work reported in NYO-1573 (Contamination of Metal Surfaces by I^{131}) was extended to solutions if I^{131}, Sr^{89}, and P^{32} and actual plumbing installations.

Significant percentages of the isotopes present in the active solutions were retained by the drain system. With I^{131} and Sr^{89}, retentions averaged 15 to 16 per cent, while with P^{32}, the average retention was close to 22 per cent. The contamination apparently resulted primarily from sorption of the isotopes on the metal surfaces.

Monitoring of selected sections and fittings in the system disclosed that the activity retained by them varied with the configuration of the part, type of metal surface involved, and nature of the isotope. In general, the more complex fittings took up more activity than did the straight sections. Brass surfaces tended to specifically adsorb the I^{131}, while P^{32} showed a strong affinity for galvanized iron. The trap tests showed that longer contact periods resulted in greater retentions.

Upon flushing with a liter of hot water, nearly 30 per cent of the retained I^{131} was washed out of the system. Better results were obtained with Sr^{89}, with removals of 30 to 40 per cent. However, P^{32} was more tightly bound, and only 12 to 22 per cent was removed with a single hot water rinse. Multiple rinses with water further reduced the residual activity, but the initial rinse was by far the most effective for each isotope.

Higher degrees of decontamination were obtained by the use of flushing solutions other than water. Nitric acid solution was extremely effective in eliminating Sr^{89} from the plumbing. High pH solutions of sodium citrate and sodium hydroxide gave similar results with P^{32}. Previous experience has shown that I^{131} can also be more readily removed by using highly alkaline solutions or detergents.

A complete presentation of the experimental results may be found in NYO-4010, "Contamination of Plumbing by Low-Level Radioisotope Wastes."

Group I. Item 4.

Retention of I^{131} and P^{32} by Bacterial Slimes

Since bacterial slimes are often present in waste drain systems, a series of studies were undertaken to explore their effect on contamination of waste line plumbing in institutions discharging radioisotope-bearing wastes.

Slimes exposed to P^{32} (as $P^{32}O_4^{---}$) for short intervals of a few minutes to two to six hours take up and hold P^{32} by simple physical adsorption in the slime matrix. The adsorption process continues in the presence of bacteriostatic agents, and at high and low pH values that depress metabolism. At longer exposure intervals, six hours or greater, the direct assimilation of phosphate by the growing bacterial film accounts for the major local concentration of P^{32} in the slimes.

P^{32} taken up during short periods of exposure by physical adsorption is relatively easily removed by rinsing while P^{32} assimilated by slimes is not washed free.

Slimes exposed to I^{131} as iodide show the following experimental results:

1. That bacterial slimes lining waste drains are capable of retaining only a relatively small portion of the I^{131} borne by liquid wastes contacting them.
2. The processes involved appear to be initially rapid physical adsorption on the surface of the slimes followed by slower adsorption of active solution by the bulk of the slimes.

3. The uptake increases exponentially with time. In the low ranges of concentration used in this study, uptake was found to be directly proportional to concentration of I^{131} in the immersion solution.
4. Thicker slimes absorb a somewhat greater volume of active solution, but slough more easily than thin, uniform coatings.
5. The iodide ion is neither metabolized nor selectively adsorbed to any appreciable extent by the slimes. Thus, isotopic dilution is ineffective.
6. Sufficient quantities of free iodine kill the bacterial slimes and increase the uptake of I^{131}.
7. Variation of pH of the immersion solutions exerts a slight effect, acid conditions favoring greater uptake. The presence of urine salts is of no importance.
8. Some metals used in plumbing installations have a stronger affinity for I^{131} than do bacterial slimes, and the slime coatings actually afford a small degree of protection from contamination to these metals.
9. Desorption of I^{131} from slimes can be fairly quickly accomplished by rinsing them with water.

Experimental results may be found in JHUX-5, "Retention of I^{131} by Bacterial Slimes in Drains."

Group I. Item 5.

Evaluation Study of Laundry Agents and Techniques Used in the Decontamination of Cotton Clothing

In its overall aspects, the removal of radioactive contaminants from protective clothing worn by workers engaged in various phases of the atomic energy program has been a costly undertaking. This is true not only because the clothing is laundered and monitored but also because the radioactive wastes resulting from the laundering operations have to be disposed of in a safe manner. While these wastes are generally of a low level of radioactivity, the nature and concentration of some decontaminating agents which have been used make them difficult to treat, either chemically or biologically. At installations where it is necessary to concentrate and store the wastes, the considerable volumes of waste produced by multiple washing and rinsing procedures have resulted in high evaporation costs.

This study was undertaken to attack the waste disposal problem at its source, in the laundry itself, rather than trying to further improve and adapt various existing treatment and concentration processes. Attention was therefore directed primarily toward:

(1) An evaluation of laundering agents used in the decontamination of clothing, with a view to employment in the laundry of agents which are effective decontaminants and still amenable to treatment by economical biological processes;

(2) A determination of techniques, including "dry cleaning" methods, affording maximum decontamination efficiency and at the same time resulting in a minimum volume of waste to be evaporated.

The radioactive contaminants used in the tests, Strontium 89, Yttrium 91, Cerium 141, Iron 59, Phosphorus 32, and Iodine 131, cover a wide range of characteristics with regard to chemical behavior and potential health hazard. They include isotopes widely used in research and therapy as well as fission products commonly encountered at the atomic energy installations. The isotopes were studied individually rather than as mixtures in order that the effects of the different agents and techniques would be more clearly delineated. Since almost all of the uniforms, coveralls, laboratory coats, and hospital bedding used up to the present in connection with radioactivity work and subjected to laundering are made of cotton in various weaves and finishes, the study was limited to the removal of contaminants from cotton cloth.

Representative complexing agents, detergents, and mixtures were tested for decontaminating efficiency to find out how specific the various agents are in their action on different isotopes and to what extent substitution of agents might be practicable in the elimination of waste treatment difficulties. The influence of wash bath temperature, strength of solution, loading of the wash-wheel, and duration of washing on decontaminating efficiency were studied. Tests were also conducted to see if particulate matter is removed more or less readily than water-soluble or precipitated contaminants, and to note the effects of level of contamination, previous laundering, soiling, starching, and wet-proofing of material by silicone treatment on ease of decontamination. In addition, the use of non-aqueous "dry cleaning" type solvents in the bulk phase of the wash bath as carriers for small volumes of immiscible aqueous decontaminating solutions was investigated.

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According to the results obtained, insoluble radioactive dusts mechanically occluded on the fabric can be satisfactorily removed by soap. However, in cases where water-soluble compounds of alkaline earths or heavy metals are deposited on the cloth, as a result of evaporation of active solution spilled or splashed on the clothing, soap tends to react with these substances and precipitate the metallic elements. The insoluble compounds thus formed adhere tenaciously to the fabric and tend to accumulate through repeated contamination-decontamination cycles. It would seem preferable, then, to use plain water in place of the soap solution to dissolve away the soluble deposits on the cloth, before proceeding with the cleaning operation.

Complexing agents are most effective in removing metallic ions strongly attached to the fibers, for they tend to form soluble metal complexes of such stability that the ions are "lifted" from the fabric and inactivated chemically.

Anionic and non-ionic detergents are of considerably less value than the complexing agents in removing metallic ions. Builders and laundering aids enhance the action of detergents in some instances, but they should be used with discretion, for adverse as well as beneficial effects may be obtained. Combinations of detergents and complexing agents should give maximum soil removal along with radioisotope removal, and should be of special value when particulate matter and greasy soil are present. High wash bath temperatures are definitely advantageous when soaps are employed, but seem to be of little or no help when some synthetics are used.

Non-metallic isotopes are most readily desorbed from cotton by alkaline solutions. Results of tests with P^{32} suggest that hydroxyl ions, when present in sufficient number, are preferentially adsorbed and displace the negatively charged phosphate ions from the surface of the cloth. In the case of I^{131}, hot water alone is capable of removing the major portion of the contamination present on cotton cloth.

Variations in laundering technique can significantly affect the performance of some agents. As a general rule, wash bath temperatures of 170° F. or higher aid in the removal of radioisotopes. Very high concentrations (3 to 6 per cent) of complexing agents and anionic detergents afford maximum removal of metallic ions, but good results can also be obtained with considerably weaker (0.3 to 1 per cent) solutions of most of the complexing agents. Light loading of the washwheel promotes decontaminating efficiency, although duration of wash does not seem to be a critical factor. An effective decontaminating agent included in the "break" should minimize cross-contamination and permit the use of a short laundry procedure. Pre-treating cloth with a water-removable finish (starch) is of no particular help, and the application of a water-repellent finish (silicone) is detrimental to decontamination.

Substitution of water-immiscible organic solvents for water in the bulk phase of the wash bath does not detract from the decontaminating ability of the various agents. Since dry cloth tends to readily absorb moisture present in the solvent

bath, intimate contact between the active ingredients in the aqueous phase and the contamination on the cloth is afforded, and only limited volumes of aqueous solution are actually required for decontamination. Sufficient water must be supplied in subsequent operations, however, to rinse away the contamination.

A complete presentation of experimental results is given in NYO-4990, "An Evaluation of Laundering Agents and Techniques Used in the Decontamination of Cotton Clothing."

Group I. Item 6.

Trickling Filter Treatment of Radioactive Contaminated Laundry Wastes

This investigation dealt with the biological oxidation of complex, synthetic laundry wastes and the concentration of radioactive isotopes in biological slimes and sludges. Rotary slime tubes, a trickling filter and agitation flasks were used to study the effects of laundering aids on organisms of the types which are utilized to purify water. The major laundry waste contaminants investigated were citrate, Versene, Igepal and seven radioactive isotopes.

The following conclusions are based upon the experimental results obtained in the biological treatment of synthetic laundry wastes contaminated with radioactive isotopes. Whenever possible the experimental data were interpreted as being equivalent to data obtainable from a six feet deep, standard rate trickling filter.

Rotating slime tube experiments indicated that a trickling filter would remove about 70 to 80 per cent of the B.O.D. from a waste which contains 500 ppm. citrate in addition to the usual amount of organic material found in an average domestic sewage. This would result in a dilution ratio of 4 parts sanitary sewage to one part laundry waste for the Oak Ridge Laundry.

The B.O.D. removal by a trickling filter would be approximately 60 to 70 per cent when the applied domestic sewage contained 1000 ppm. citrate and the pH was adjusted to 7.0.

A trickling filter would probably remove about 40 to 60 per cent of the applied B.O.D. if the waste, adjusted to pH 7.0, contained 2000 ppm. of citrate in addition to at least the minimum amounts of domestic sewage solids or nutrients required to support biological growth. Such a waste would contain approximately 1000 to 13,000 ppm. 5-day B.O.D.

Versene concentration of as much as 250 ppm. in an influent would probably cause a collapse in the slime structure and inadequate performance of a trickling filter.

A waste containing 1000 ppm. of Igepal, when diluted by a factor of four with domestic sewage, would probably not interfere with trickling filter operations. The Igepal would cause some foaming but would most likely pass through the trickling filter bed without changing its chemical form.

Concentrations of 10 ppm. active ingredients, of Tide or of Rinso would not interfere with trickling filter slimes; however, as much as 100 ppm. would probably reduce the efficiency of a well designed and operated plant as much as 15 per cent.

Although Igepal did not appreciably hinder waste treatment, its effects on aquatic life need to be investigated before accepting it as the laundering detergent which is least likely to cause eventual stream pollution.

Various laundering aids did not directly influence the removal of radioactive isotopes by biological cells as long as environmental conditions supported a thriving biological community. Negligible amounts of Sr^{89}, Cs^{134}, Ru^{106}, and I^{131} would be

detained by the direct action of slimes at a pH of 7.0. About 20 per cent of the total phosphorus would be detained in a trickling filter if the pH of a solution was 7.0 and the total initial phosphorus concentration was 30 ppm.

If domestic sewage containing stable and radioactive phosphorus not exceeding 30 ppm. were agitated in a batch treatment process, as much as 95 per cent of the phosphorus would be removed from solution during the period of biological growth; however, upon lysis of the cells, the phosphorus in the organism would again revert to soluble inorganic phosphorus.

About 30 to 50 per cent of the Ce^{144} would be removed by a trickling filter slimes if the influent pH was 7.0. If either Sr^{89} or Ce^{144} and domestic sewage were agitated in a batch treatment process until the pH became slightly alkaline during the biological growth phase, virtually all of the Sr^{89} and 85 per cent of the Ce^{144} would be adsorbed to the cell structures. The adsorbed Sr^{89} and Ce^{144} would remain on the cells even though the cells died and became part of the accumulated debris.

A complete presentation of experimental results is given in NYO-4514, "Trickling Filter Treatment of Radioactive Contaminated Laundry Wastes."

Group I. Item 7.

Disposal of Radio-Isotopes in Institutional Incinerators

This study deals with the development of methods and techniques for measuring the amounts of radio-isotopes on the stack walls, in the ashes and in the stack gases and atmosphere during and after incineration of contaminated combustible material in conventional institutional incinerators. Controlled experiments were conducted with P-32, I-131, and Sr-89. It was found that about 90% of the P-32 and Sr-89 remains in the ashes where it may constitute a hazard during ash removal and disposal. Although 80% of the I-131 is discharged from the incinerator with the stack gases, atmospheric pollution is not the critical problem because, before undesirable atmospheric concentrations are reached, the I-131 appearing in the ashes greatly exceeds amounts which can be handled safely.

The experimental data have been employed to formulate suggested standards for the safe incineration of P-32 and I-131. The maximum permissible charging rate is 4 microcuries of P-32 per pound of refuse burned per hour and 2 microcuries of I-131 per pound per hour. Both of these maximum charging rates are controlled by the hazard of breathing dust during ash removal operations.

A complete presentation of the experimental results is given in NYO-4517, "Behavior of Institutional Incinerators When Used to Burn Radioactive Wastes."

Group II. Item 1

Survey of Ocean Disposal Practices in The Atomic Energy Industry

This survey was made to determine how well grounded our relatively small sea dumping operations were, and what elements from this existing experience might be projected to the design of reactor scale operations. We visited the principal installations on the Atlantic and Pacific coasts, discussed practice with responsible officers of A. E. C. contract works, and sought the opinions of leading oceanographers, marine geologists, and ecologists.

This preliminary survey showed that only casual use was being made of oceanographic information, that existing practice had developed as a working expedient to take advantage of local resources. The methods of disposal used for low level wastes were clearly inapplicable to the kinds of wastes anticipated from a developing reactor power economy. We also learned that oceanographers were unaware of the waste problems associated with the fission industry.

A comprehensive report of the survey is given by a paper, "Technical and Economic Aspects of Disposal of Radioactive Waste at Sea," by J. M. Morgan, A. E. C. publication WASH-275. Further discussion of the findings are to be found in A. E. C. TID-7517, "Ultimate Disposal of Radioactive Reactor Wastes in the Oceans," C. E. Renn, and in "Disposal of Radioactive Wastes at Sea," C. E. Renn, Vol. 9, p. 718, International Conference on Peaceful Uses of Atomic Energy, U. N. 1956.

Group II. Item 2.

Survey of Land Burial Practices in the Atomic Energy Industry

In 1953-1954, the U. S. Atomic Energy Commission installations practicing land burial were visited to determine the policies concerning land burial for the disposal of radioactive wastes.

A careful survey was made of the types of waste and activity of the waste disposed of by burial. This included a consideration of the type of packaging deemed necessary, the method of packaging, the transportation used to carry the packaged material to the burial ground, the method of burial, the safety requirements for operating personnel, the amounts of material and activity buried and the method of inventoring the stored and buried wastes.

There was found to be no uniform policy and that each installation had established its own criteria. In general, the wastes were concentrated and wrapped or packaged for storage or burial. The packaging was minimal; the only principal requirement appeared to be containment and sufficient package strength for handling and transportation. Records were kept of gross volumes buried; radiations are noted only insofar sa pertains to personnel exposures and no measurements were made for more than an estimate of the curie content.

A detailed report of the survey was made in interim reports to the A. E. E. and a summary report is given in A. E. Cl publication NYO-7830, "Radioactive WAste in the atomic Energy Industry."

Group II. Item 3.

Cost Survey of Radioactive Waste Disposal Practices In the Atomic Energy Industry

This survey was made in conjunction with the surveys of Ocean Disposal and Land Disposal practices. A "house to house" survey was made on methods and related costs of disposing of radioactive wastes as practiced in 1955 by twelve atomic energy installations. The large production sites were omitted from this survey. The methods by which radioactive wastes are disposed of was found to depend upon the geographic position of the particular installation and other peculiarities. Installations in more populous areas get rid of their wastes by transporting them to more remote areas; installations in sparcely settled locations dispose of their wastes on site. In general, installations on the seaboard utilize oceans while those inland favor land disposal.

The costs reported represent the best information available at the time of the survey. In many cases they are based on estimates of man hours, equipment hours, or number of containers of waste. Cost per unit volumes are reported because volumes were the only readily obtainable measure of the wastes. Many variables were found to influence these unit costs. Some of these were state health and safety regulations, availability of diluting waterways, geological conditions, chemical and radiochemical composition of the wastes, and, of course, the size of the operation. Costs per unit volume should not be used to compare installation efficiencies because each installation operated under a different set of circumstances.

The costs found are summarized in the following tables. A complete presentation of the survey is given in NYO-7830, "Radioactive Waste Disposal Practices - A Survey of the Costs."

Installation	Collected after Monitoring	Transferred in Containers	Radioisotope Concentration Treatment				Effluent Discharged		Stored in Underground Tanks
			Evaporated	Chemically Precipitated	Ion Exchanged	Concentrate Produced	To Surface	To Subsurface[1]	
Argonne Nat Lab.	5,732[2]	176	66	25	1.9		46,400	500	none
Bettis Field (WAPD)	1,679[3]	79	1,600	none	none	3.96	137,000	none	none
Brookhaven Nat L.	3,267[4]	1.2	367	none	none	3.67	120,000	none	none
Fernald (FMPC)				none	none		94,000	none	none
Knolls At. Pow. Lab.	1,130	5	1,125	none	none	4.9	126,000	none	42
Los Alamos	13,900	none	none	13,900	none	33.2	13,900	none	none
NRTS (CPP)[5]	671	none	252	none	none	3.56	none	671	3.56
Oak Ridge (ORNL)	1,000	none	none	none	none	none	158,000	1,000	none
Rocky Flats	4,800	none	none	1,570	none	45.5	40,000	786	none

(1) Discharged either to a surface holding pond or directly to subsurface.
(2) Does not include high level wastes collected in "pots".
(3) Does not include wastes dumped to sewer system.
(4) The quantity monitored was between 367,000 and 120,000,000 gallons.
(5) The quantities listed are for a 6 month period. They would not be true for a 12 month period if doubled because waste production varied.

Table I Volumes of Liquid Wastes Handled (by stages) During Fiscal Year 1955 (Units in 1000's gallons)

Installation	Wastes Treated (1000 gal)	Gross Cost of Concentration	Concentration Cost Per Gallon	Operating Cost[1]	Operating Cost Per Gallon	Concentrate Produced (gallons)	Concentrate Packaging Cost	Concentrate Packaging Cost Per Gallon	Concentrate Shipping Cost[2]	Cost of Underground Storage Facilities[3]	Summary Cost = Concentrating Packaging Shipping &/or Storing Costs	Unit Summary Cost (per gal.)
NO TREATMENT GIVEN												
Oak Ridge (ORNL)	1,000	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	$ 85,400	$0.085
BY EVAPORATION												
Argonne Nat. Lab.	66	$	$	$	$		$	$	$	$	$	$
Battle Field (WAPD)	1,600	56,060	0.04	37,510	0.023	3,960	3,110	0.79	3,150	N.A.	62,320	0.039
Brookhaven Nat. L.	367	62,400	0.17	12,230	0.033	3,670	770	0.21	830	N.A.	64,000	0.174
Knolls At. Pow. Lab.	1,125	60,900	0.05	8,500	0.025	4,900	860	0.36[4]	610[5]	2,400	64,770	0.057
NRTS (CPP)[6]	252					3,565	N.A.	N.A.	N.A.	8,200		
BY EVAPORATION AND CALCINING												
Fernald (FMPC)		718,141		328,831			N.A.	N.A.	N.A.	[7]		
BY CHEMICAL PRECIPITATION AND VACUUM FILTRATION OF SLUDGE												
Argonne Nat. Lab.	25											
Los Alamos	13,900	136,840	0.01	75,630	0.005	33,200	nil[8]	nil[8]	1,870[9]	N.A.	138,710	0.010
Rocky Flats	1,570	126,120	0.08	66,870	0.043	43,000	4,140	0.10	5,940	N.A.	136,200	0.087

N.A. signifies "not applicable".
(1) Total treatment cost minus fixed cost.
(2) Estimated as a proportion of the gross weight or volume shipped.
(3) Construction unit cost of storage facilities multiplied by annual input. Does not include operational and maintenance costs.
(4) Only 2,400 gallons packaged.
(5) Theoretical cost of shipping 2,400 gallons to ORNL. (21,800 lbs at $2.8¢/cwt.)
(6) The quantities listed are for a 6 month period. They would not be true for a 12 month period if doubled because waste production varied.
(7) Construction unit cost is $1.61 per cu. ft.
(8) Used drums are obtained from other operations on the site.
(9) The cost of hauling and burying the sludge.

Table 2 Costs of Liquid Waste Treatment and Waste Concentrate Disposition Operations
Fiscal Year 1955

Installation	Waste Collection			Waste Concentration					Waste Packaging			Shipping and Terminal Handling Data					Overhead	Total Known Cost	Total Cost per cu. ft Collected
	Volume (cu. ft.)	Cost	Unit Cost	Method	Volume in cu. ft Before	Volume in cu. ft After	Cost	Unit Cost[1]	Volume (cu. ft)	Cost	Unit Cost	Destination	Overland Distance (miles)	Volume (cu. ft)	Cost	Unit Cost			
Argonne Nat Lab.	14,290	$ 18,530	$ 1.30	baling	10,000	2,380	$2,580	$ 614	6,660	$11,330	$1.70	Oak Ridge	530	6,660	$3,460	$0.52	$12,230	$48,270	$3.38
Bettis Field (WAPD)	18,000	3,760	0.21	incinrn	13,200	360	4,510	123	710	2,530	3.56	Earle, N. J.	370	710	3,440	4.84	3,320	17,560	0.97
Brookhaven Nat L.	16,140	6,520	0.40	baling	2,000	640	1,190	380	745	2,650	3.55	Floyd Bennett Field	70	745	1,030	1.38	6,740	18,130	1.12
Knolls At Pow Lab	36,880	7,910	0.21	baling	20,000	3,300	5,170	861	20,950	17,840	0.85	Lake Ontario St Area Oak Ridge	300 850	6,980 13,970	2,735 5,470	0.39 0.39	13,320	53,445	1.45
Los Alamos	62,400	32,030	0.51	none	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	Site burial	-	62,400	8,970	0.14	14,960	55,960	0.90
NRTS, Idaho	27,000	6,280	0.23	none	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	Site burial	-	27,230	9,900	0.36	4,620	20,800	0.77
Oak Ridge	116,400[2]	38,440	0.33	none	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	Site burial	-	116,400	25,830	0.22	28,900	93,170	0.80
Rocky Flats	N.A.	N.A.	N.A.	none	N.A.	N.A.	N.A.	N.A.	33,900	15,380[3]	0.45	NRTS, Idaho	700	33,900	35,390	1.04	2,700	53,470	1.58
U of Cal Rad Lab Berkeley	6,200	3,610	0.58	none	N.A.	N.A.	N.A.	N.A.	6,180	11,330	1.83	San Francisco	20	6,180	4,850	0.77	11,290	31,070	5.01
Livermore	4,260	3,520	0.83	none	N.A.	N.A.	N.A.	N.A.	4,160	8,640	2.08	San Francisco	50	4,160	3,550	0.86	8,910	24,620	5.78

N.A. signifies "not applicable"
(1) Concentration unit cost measured in dollars per unit of concentration.
(2) For 12 months based on 6 months of record.
(3) Materials only.

Table 3 Costs of Low Level Solid Wastes Disposal Practices
Fiscal Year 1955

Installation	Collection (and Storage)			Packaging			Shipping and Terminal Handling Data				Capital Investment Depreciat'n Charged[1]	Overhead	Total Known Cost[3]	Total Cost per cu. ft. Collected
	Volume (cu. ft.)	Cost	Unit Cost	Volume (cu. ft.)	Cost	Unit Cost	Destination	Volume (cu. ft.)	Cost	Unit Cost				
Argonne Nat. Lab.	391	$10,440[2]	$ 26.70	N.A.	N.A.	N.A.	Site storage	N.A.	N.A.	N.A.	$ 10,260	$ 100	$10,540	$ 27
Bettis Field (WAPD)	26.8	900	33.60	26.8	$23,930	$ 893	Earle, N.J.	26.8	$10,600	$ 392	none[4]	3,510	38,940	1,450
Brookhaven Nat. L.	462	3,600[2]	7.80	462	4,200	9	Floyd Bennett Field	462	1,620	3.52	1,420	4,870	14,290	30
Knolls At. Pow. Lab.	5.6	2,900[2]	518.00	N.A.	N.A.	N.A.	Site storage	N.A.	N.A.	N.A.	1,950	300	3,200	572
NRTS, Idaho	230	600	2.61	N.A.	N.A.	N.A.	Site burial	230	80	0.36	none[4]	375	1,055	4.58

N.A. signifies "not applicable".
(1) Cost of maintaining and guarding high level wastes in storage represents an additional cost not included.
(2) Includes amortization of construction cost of storage facilities.
(3) Sum of collection, packaging, shipping and overhead costs.
(4) Some of the depreciation charged to low level wastes practices could be charged here.

Table 4 Costs of High Level Solid Wastes Practices

Fiscal Year 1955

Group II. Item 4.

Stream Survey in the Uranium Mining and Milling Areas of the Colorado Plateau

In the summer of 1958, from June through August, a field study sponsored by the Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, under an Atomic Energy Commission contract was undertaken in the Colorado Plateau area of the United States. The purpose of the study was to investigate surface water contamination arising from uranium mill recovery operations.

Rapid stream reconnaisances from 1950 to 1956 by state and federal agencies in the vicinities of uranium milling operations in Arizona, Colorado, New Mexico and Utah have indicated a need to study closely the effects of discharges from these industrial operations on the environment. All surveys heretofore have been concerned solely with the radiological implications of the problem. This study was concerned as well with the physical, chemical, bacteriological and aquatic characteristics of the surface waters above and below certain mills.

The focus of stream investigation was located in the City of Grand Junction, Colorado, which lies near the Utah border on the western slope of the Rocky Mountains at the confluence of the Colorado and Gunnison Rivers. The survey included stretches of the Colorado River from near Cisco, Utah to Glenwood Springs, Colorado, and from Grand Junction to the Town of Gunnison, Colorado, on the Gunnison River.

The following milling plants were included in the survey: Climax Uranium Company, Grand Junction, Colorado; Gunnison Mining Company, Gunnison, Colorado; and, Union Carbide Nuclear, Rifle, Colorado.

There are a number of different ore processing methods employed to remove uranium from the parent material. The three plants concerned in this survey all employed the solvent extraction process. Processing the ore involves crushing, grinding, roasting and digesting or leaching to cause the uranium to go into solution. pH is adjusted and the liquors may be heated. The steps described are followed by the separation and precipitation of uranium salts. Some vanadium may also be precipitated and certain fractions may enter the waste streams.

Waste sources include wash water, sands and solids and the filtrate which follows precipitation. Often waste products are lagooned in tailing ponds. Solids settle out. Waste liquors either evaporate, seep into the ground and enter ground water or are discharged directly into nearby receiving streams thereby causing direct surface water contamination.

Types of Samples

In order to determine the physical, chemical, radiological, bacteriological status of the stream, several types of samples were taken. Sampling included collecting quantities of water, river muds, algae and other insect life.

Under chemical analysis the following determinations were made on water samples:

pH	Phen. Alkalinity	Methyl Orange Alkalinity
Sulfates	Calcium	Biochemical Oxygen Demand
Copper	Magnesium	Nitrates
Chromium	Silica	Arsenic
Iron	Chlorides	Selenium
Manganese	Fluorides	Uranium (U_3O_8)
Sodium	Ammonia	
Vanadium (V_2O_5)	Dissolved Oxygen	

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In the bacteriological determinations, only the total bacteria count and the coliform count were made.

Physically, the water samples were routinely checked for:

Temperature
Turbidity
Color
Suspended Solids
Dissolved Solids

Gross alpha and beta determinations of dissolved and suspended solids in water samples were made. Gross alpha and beta determinations were also made in order to investigate the uptake of muds and algae. Radium (soluble) determinations have not been made to date because of lack of funds.

The report for the Commission is being prepared and it is estimated that it will be available for publication by 1 June 1959.

It is understood that budget limitations will not permit this study to be carried on during the coming summer.

Group III. Item 1.

Conferences on Ocean Disposal of Radioactivity and Fission Wastes

In the late summer of 1954, a first conference on ocean disposal of radioactive and fission wastes was arranged by the study group through the cooperation of the Woods Hole Oceanographic Institution. At this meeting, specialists from the Atomic Energy Commission and contract projects presented information on the properties and potential quantities of wastes to a group of leading oceanographers from the Eastern Atlantic area.

After an exchange of minutes and mail comment, a memorandum representing the problems projected by waste engineers and the comments of oceanographers was prepared and sent to the principals for study.

On June 22 and 23, 1955, a second conference for a more informed examination of the problem was held at The Woods Hole Oceanographic Institution. The praticipants included most of the leading physical and chemical oceanographers, and marine geologists and ecologists in the United States, as well as waste disposal specialists associated with the Atomic Energy Commission operations. Members of the Woods Hole Oceanographic Institution, The Scripps Institution of Oceanography of the University of California, The Lamont Geophysical Laboratories of Columbia University, and the Chesapeake Bay Institute of The Johns Hopkins University, presented prepared discussions. Forty research engineers, oceanographers and marine scientists took part in the conference.

From this conference the following conclusions were drawn.

First, it would appear quite practical to design ocean disposal operations for specific conditions. The seas offer many different systems that may be exploited if there is concurrence of local advantages. The working problem is that of framing the question so that oceanographers can give definite answers. It may be possible to explore disposal potentialities empirically in some areas; such practical experiments are desirable to determine if mechanisms for natural removal of radioactivity by settling materials can be utilized.

Second, disposal of free wastes by dilution will require further studies of local mixing patterns in the sea. It cannot be assumed that any large fraction of the oceans' volumes can be used in dilution processes -- all experience points to the contrary view. Most liquid wastes will spread and mix rapidly along horizontal strata of comparable densities and viscosities, but vertical mixing into waters of differing characteristics is much slower. We know this from mixing experience with wastes discharged into lakes, harbors, and slow flowing rivers.

The most economical device, that of discharging high salinity, high density wastes near the sea surface, with the expectation that these fluids will sink with little mixing to the deeps is unpromising. Surface discharged, heavy industrial wastes show a high degree of mixing during passage through the relatively turbulent upper hundred meters, where reconcentration by plankton is most likely.

Third, it may be practical to contain dense, free wastes in sequestered water masses of some of the ocean's deeps. The most promising deep water masses for waste confinement are those that are surrounded by high rims, shelves, or sills. A number of such well bounded deeps have been described by submarine geologists -- their accessibility is obviously an important consideration.

It is necessary to establish the separateness and integrity of these confined masses, and to determine the rates at which the enclosed waters may be exchanged with the surrounding masses. Few of the recognized "deeps" have been studied in sufficient detail to permit useful waste disposal design. The discharge of a fraction of the projected waste production for the next fifty years in some of these may produce thermal convection mixing and project mixed wastes into the overlying waters. This possibility requires a careful study of thermal stability of the water mass, and of thermal loading limits.

Oceanographers do not agree on the rates at which the major ocean masses mix. Some studies indicate deep water ages in the Atlantic to be in the order of two thousand years -- that is, the deep water was displaced from the surface about two thousand years ago. Other investigations suggest that overturn may be much more rapid, and that the seas' stability is conditioned by climatic cycles.

Fourth, heavy solidified wastes, or encased wastes may be effectively buried in limited areas of the sea floor. We currently dispose of small amounts of low level laboratory wastes by casting them in dense concrete cylinders or blocks, and dropping them in

dump areas. It is commonly believed that such drums and massive packages penetrate or settle into soft, indefinitely deep, bottom ooze, and are forever locked up in the sea floor. This is an erroneous conception; the rates of silt accumulation in most parts of the sea beyond the continental shelf are very low, the ooze layer is thin, and the bottom is well consolidated and unyielding. Our experience with wrecks and sunken bodies in harbors and estuaries shows us how slowly heavy objects settle in even poorly consolidated sediments.

There are, however, a number of well defined, enclosed basins of marine mud where penetration and burial is possible. Some of these lie on the continental shelf, close to land. These deposits exist because they are bounded by firm walls, and there is little chance of density flows or mud slides in such mechanically limited areas. To utilize these areas precision navigation and spot coring explorations may be required.

Fifth, it is very clear that microscopic marine life, the plankton, will concentrate fission products from contaminated waters, and that the assimilated wastes will be further concentrated in the tissues of predatory animals. The level of radioiodine that may be achieved in a major sea waste disposal operation may be directly damaging to plankton and small animals. Less is known about the metabolism of strontium and cesium by marine animals, but it has been observed that these isotopes build up in plankters that feed by filtering. The possibilities of seriously contaminating the marine food supply makes it essential the wastes be kept from fertile waters.

It can be shown that mixing wastes of the magnitudes contemplated in a reactor power economy with the volumes of the oceans will appreciably raise the background of the seas. The more important feature of this enrichment is not the total increase in activity, but the high local concentrations of more toxic fission products that must occur during loading to equilibrium levels. Along with strontium and cesium, the system will contain a variety of daughter elements, the biological properties of which are unknown, some of these will be much longer lived than the more active parent materials.

This last group of factors points out a requirement that we must meet if we are to discharge a significant fraction of our reactor produced wastes into the seas. We must establish acceptable levels for added fission products in the various marine systems. The standards used for drinking water cannot apply here, since we are not concerned with the direct intake of sea water, but with a much more complicated series of cycles terminated by concentration in food materials, and possibly in the chemical and ore resources of the seas.

The complete paper, "Ultimate Disposal of Radioactive Reactor Wastes in the Oceans," C. R. Renn, was presented at the Nuclear Engineering and Science Congress, sponsored by the Engineers' Joint Council of the American Institute of Chemical Engineers, in Cleveland, Ohio, Dec. 1955.

Group III. Item 2.

Conferences on Land Disposal of Radioactivity and Fission Wastes

The response and interest of the oceanographers and related scientists to the problem of waste disposal was so enthusiastic that A.E.C. officials felt that a similar conference to acquaint earth scientists and scientists from related disciplines with the problems of high level radioactive waste disposal would arouse their interest and suggest possibilities of disposing of these highly active wastes within the earth. On Nov. 15, 1954, a conference was held in Washington, D. C. to provide preliminary background information on the problem to key members of the earth scientist group.

Many suggestions were advanced by the group but it was felt that exposure to the problem should be extended to other members of the earth scientist group who were specialists in areas which showed promise for waste disposal. At this time a further meeting was planned which would include a larger number of scientists, whose interest and experience would cover all of the fields of earth science pertinent to radioactive waste disposal.

The Earth Science Division of the National Research Council was approached and agreed to participate in a conference on radioactive waste disposal. A steering committee appointed by the NRC met with staff members of The Johns Hopkins University, Department of Sanitary Engineering, and A.E.C. engineers in an organizational meeting on April 15, 1955.

This resulted in the NRC meeting of the Earth Sciences on Radioactive Waste Disposal, at Princeton, N. J. on September 10, 11, 12, 1955.

Group III. Item 3.

Symposia on A.E.C. Waste Disposal Research

The Department of Sanitary Engineering has served as hosts for two symposia held by the A.E.C.

One: The second sanitary engineering conference, April 15-16, 1954.

Two: The Working Meeting on Fixation of Radioactivity in Stable Solid Media. The Hopkins study group served as a staff group in the organization of these meetings, took minutes of the meeting, and reported the papers and discussion given during the symposium.

These are found in A.E.C. publications WASH-275, Sanitary Engineering Conference, Baltimore, Maryland; and TID-7550, "Fixation of Radioactivity in Stable, Solid Media."

Group IV. - Item 1.

The Sorptive and Zeolitic Properties of Natural Water Borne Silts

The increasing rate of production of radioactive materials and the widening uses of these substances by the military, by research organizations and industries, produce many unique problems concerned with the disposal of radioactive wastes. Naturally, a great deal of effort has been expended in preventing the human environment from becoming contaminated to hazardous levels. Despite these efforts, however, there always will remain a finite probability that lethal quantities of radioactivity will be released into the environment. Once present there, the problem is largely of what will happen to it. What properties of the environment will act to control the dispersion and ultimate distribution of the waste? Is it feasible to attempt to alter these properties in an attempt to reduce the hazard? Obviously information from a variety of sources will be needed before questions of this sort can be answered.

Within the division of our environment into aquatic, terrestial, and atmospheric, the aquatic fraction stands out as the part that has the greatest likelihood of becoming contaminated to the point that the normal uses will become much limited. Many of our major cities are located on the seaboard or on waterways that communicate to the sea. The major installations of one branch of the military are by necessity located in coastal areas. Thus, enemy action involving the use of atomic weapons against these regions quite probably would contaminate a part of our aquatic environment. An accidental release of activity from any one of several of our reactor installations could reduce the usefulness of the waterways on which they are located. Finally, the oceans have often been suggested as dumping

grounds for radioactive wastes, a choice that has been made largely because of the size and apparent remoteness of the abysmal depths rather than from information which would show that the behavior of the marine environment will forever keep the waste from becoming a hazard.

The studies that are reported here were undertaken with the hope of being able to learn something of the future and magnitude of the interaction of radioactive wastes and a part of the aquatic environment--the suspended solids that are present in all natural waters. This is recognized as being only a part of the overall picture but the results of many other studies have emphasized the fact that sorption reactions are the rule rather than the exception when extremely dilute solutions, as are many radioactive waste solutions, come in contact with solid surfaces. These considerations suggest that under many conditions that are found in nature, knowledge of the extent to which soprtion reactions occur will be important in assessing how fast a waste will be dispersed and in predicting its ultimate distribution in the environment.

A two-fold objective has guided these studies. The first was to obtain detailed information regarding the extent of the reaction between a limited number of radio isotopes and several natural solids. The second was to attempt to find the limited number of systems studied patterns of behavior that might be extended to other systems using analogous chemical or physical properties as the basis for extrapolation.

Isotopes were chosen for study that would be representative of as large group of elements as possible or of different uses of radioactive substance. Phosphorus, iodine, and sulphur would normally occur as, or would be rapidly converted to anions in waste solutions. They are widely used by research groups and the disposal of wastes from these operations might under some conditions create a hazard. The anions of

phosphoric acid can occur as mono-, di-, and trivalent ions, depending on the pH. Strontium, iron, and copper are usually cationic in solutions. Strontium is one of the fission product elements and its chemical behavior is similar to that of calcium. The limitations imposed by a laboratory equipped only for tracer studies prevented the use of many isotopes, especially several long half life species, that might have been better suited for these purposes, but were not used because of the potential hazard to the experimenters.

The solids that were studied are representative of several kinds of substances found suspended in natural waters. A series of materials taken from cores obtained in Chesapeake Bay had been characterized by mineral and X-ray analyses in a study of Bay sediments carried on by the Chesapeake Bay Institute of The Johns Hopkins University. A sample of sediment from the Roanoke River in Virginia was studied with only size analysis as a solid characteristic. Samples of commercial Bentonite and Fuller Earth were studied, as were several size fractions of powdered Pyrex glass.

In all of the studies the following environmental factors were either controlled or measured; pH, temperature, concentration of suspended solids and reacting dissolved substances, and ionic strength.

The uptake of phosphorus is maximum in the pH range in which the $H_2PO_4^-$ ion predominates. An uptake mechanism involving a rapid adsorption process and a slow diffusion process was suggested.

Strontium, copper, and iron (III) will precipitate from solution as basic salts under appropriate conditions. Added solids act as a "sweeper" aiding the removal of finely divided precipitate. When conditions for precipitation have not been met, added solids remove these dissolved substances by adsorption and can effect a more complete removal than can

be achieved by precipitation.

There is very little reaction between iodide and suspended solids.

Sulphur is adsorbed in the pH range favoring the formation of HSO_4^- ion. The removal of bisulphate by an adsorption mechanism during a 1,000 million (10^9) variation in sulphur concentration was demonstrated.

A complete presentation of experimental data and conclusions is given in A.E.C. Publication NYO - 4591,"The Sorptive and Zeolitic Properties of Natural Water Borne Silts."

Group IV - Item 2

Disposal of Fission Wastes by Adsorption of Long Lived Isotopes on Soil-Sawdust Beds

Cellulose and lignin and various soils and clays adsorb strontium, cesium and a variety of other metals. The amounts that can be bound by adsorption vary with the conditions of contact.

European investigators have issued favorable reports of the possibilities for removing the long lived strontium and cesium from mixed fission products of reactor type wastes by passing the wastes through sawdust, beds of shavings, etc.

This investigation checks the practical limitations of such inexpensive natural adsorption materials as soil and sawdust, straw, and peat, in which the materials are allowed to decompose as in deep soil burial. The soil is used principally as an inoculum and buffer. During decomposition, the more soluble organic fractions are fermented to leave the stable fractions and microbial materials. At the same time nitrate salts are reduced by the oxygen consuming bacteria.

The combination of reactions occurring during soil storage of sawdust wetted with fission wastes results in a substantial increase in the adsorption of strontium, cesium, and of the difficultly adsorbed long lived ruthenium ion. This last metal evades most zeolites. It is believed that ruthenium combines with organic materials of the bacterial cells produced during anaerobic fermentation of the soil-sawdust composts.

The fermentable components of sawdust do not fully reduce nitrates present in representative wastes. It is necessary to dilute wastes roughly ten times to secure active fermentation. The gas produced

by nitrate reduction requires that the bed be maintained under high hydrostatic pressure, or that systematic ventilation be developed to prevent explosion. Sodium salts in fission wastes limit the composting process by producing high pH values as denitrification proceeds.

Group IV. - Item 3

Study of Uptake of Ruthenium in Fermenting Organic Materials

Ruthenium in fission products is poorly adsorbed in soils. This is due to the fact that the element in solution exists as cations, complex anions and neutral oxides, after it has been in contact with concentrated nitric acid.

In biological reducing systems metals with properties like ruthenium are precipitated and adsorbed. This project is designed to discover if cheap waste materials prepared as composts, may be developed as such biological reducing systems where ruthenium may be reduced on surfaces of bacterial cells and on other strongly reduced components of anaerobic soil-organic systems.

This work is incomplete. Findings to date show that ruthenium is not taken up on fresh sawdust, but that it is bound in increasing concentrations as the sawdust is allowed to rot in anaerobic soil-sawdust materials.

The final studies of this and Item 2 are now under way and it is planned to write a terminal report to the Atomic Energy Commission on or before May 1959.

Group IV. - Item 4.

Removal of Ruthenium from Solution

The ruthenium "problem" is primarily due to the fact that the element in solution exists as cations, complex anions, and neutral oxides, after it has been in contact with concentrated nitric acid. It is highly improbable that a single absorbent could be used to eliminate all these forms.

However, if reduction to the metallic state could be achieved, the complete insolubility of the latter should provide for a satisfactory factor of decontamination.

We have shown that a solution containing 5 ppm. of ruthenium obtained from strong nitric acid media, in .001 M sodium sulfate solution, is completely reduced on a stainless steel cathode. The ruthenium containing solution at a rate of 60 ml. per minute was passed through a 180 ml. cylinder provided with rotating stainless steel discs. Under these conditions, 100 percent of the ruthenium was removed as indicated by a sensitive colorimetric test.

These results prove that if ruthenium as an anion, or as a neut molecule can be brought in contact with a cathodic surface, reduction to th metallic state takes place.

We are at present redesigning a porous cathode for large volum experiments at fast rates, and plan to follow the loss of ruthenium by radioactive counting techniques.

Group IV. - Item 5.

Separation of Cesium and Strontium from Alumina Wastes Obtained from the Fluid Calciner

The fluid calciner, operating at temperatures 400° C. - 450° C., gives a solid product upon which the cesium and strontium are very closely held. Leaching with hot water removes only small amounts of the strontium. In order to decontaminate this solid of both of the above mentioned nuclides, it was found necessary to dissolve the alumina in either NaOH or $(C_2H_5)_4$ NOH. These alkaline solutions when subjected to an electric current using moving mercury as a cathode and a rotating graphite anode, furnished a product exhibiting a decontamination factor of 10^6 for cesium as measured by the flame photometer. To achieve this degree of removal of either the cesium or strontium it is necessary to continue the addition of NaOH solution in order to maintain a constant current. The ammonium base is not removed by electrolysis in the mercury cathode, thereby maintaining a constant current.

The cesium or strontium amalgam is continuously decomposed by colloidal silicic acid sols, thereby producing suitable materials for the production of the corresponding crystalline alumina silicates.

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Group IV. - Item 6.

Artificial Clays for the Fixation of Radioactive Nuclides

The fixation of cesium and strontium into non-leachable, and non-volatile compounds is a major problem in atomic waste disposal. The chemical nature of these two elements makes it exceedingly difficult to place them into compounds where both elements are insoluble in water.

Crystalline alumina silicates of feldspatic or leucite structures satisfy the above specification. Heretofore, the methods of preparing such crystalline substances required extremely high temperatures or long periods of digestion in an autoclave. We have found that if the silica and alumina are in a colloidal state of extreme subdivision; that the cesium in the form of cesium silicate, or the strontium in the strontium silicate form, combine at 100° C.,to produce insoluble forms of cesium and strontium. Upon standing at temperatures from 200 - 300° C., or if heated to 1000° for a few hours; the amorphous mass crystallizes into definite compounds. These changes have been followed by X-ray diffraction measurements.

A more extensive discussion is given in a paper in TID-7517 , part 1b, "Sanitary Engineering Aspects of the Atomic Energy Industry," Page 368, entitled, "Use of Artificial Clays in Removal and Fixation of Radioactive Nuclides."

Group V. - Item 1.

Feasibility of Establishing a National Burial Ground for Radioactive Wastes in The Northeastern United States

Accumulating every day at Atomic Energy Commission sites, private and government laboratories and at university as well as medical research centers are considerable volumes of radioactively contaminated materials. The waste materials may be in the solid, liquid or gaseous state and are classified as either combustible or non-combustible. Liquid and gaseous waste may be fixed in the solid form by a number of processes in preparation for disposal of them by burial.

The volume and tonnage of this unwanted and useless material is large, and the fact that the waste must be painstakingly handled and monitored, safely packaged, and often transported long distances combine to make the entire disposal operation costly and time consuming. Handling, transporting and processing the material requires careful control to protect employees from industrial hazards.

There exists a pressing need for economical methods of disposing of all types of radioactive waste. Land burial is the most economical method so far devised for sequestering the waste products under consideration. The purpose of a land burial ground is to immobilize waste materials permanently in a controlled location thereby reducing environmental hazards. Isolation is accomplished by the sanitary land-fill method in trenches or cells at sites selected for favorable geologic, hydrologic and meteorological conditions. Any selected burial area removed from the confines of current Commission operating and production sites should have a capacity to satisfy burial requirements for many decades.

Commission regulations* permit "on-site" burial of very small quantities of radioactivity under certain conditions. These regulations do not limit the burial of waste at any of the five currently operating major burial areas which are under the jurisdiction of the prime A.E.C. contractors. On-site burial at other locations is extremely limited. Only one major operating site in the East, the Oak Ridge National Laboratory, accepts waste for burial from off-site operations.

Several large producers of radioactive waste are located in the northeastern United States. These include Knolls Atomic Power Division, Brookhaven National Laboratory, Argonne National Laboratory, Mounds Laboratory and Westinghouse Atomic Power Division. Smaller producers in the area include hospitals, university research centers and commercial firms. The major portion of the waste is transported by rail or truck to Oak Ridge National Laboratory for land burial; a small volume is buried at sea off the coasts of Massachusetts, New Jersey and Virginia. There have been occasions when waste awaiting shipment has been temporarily stored at the Lake Ontario Storage Area near Lewiston, New York.

Based on the information currently available, approximately 1,000 tons or 4,000 cubic yards of low and intermediate level waste accumulates yearly in the northeastern portion of this country. It has been estimated that the annual solid volume of this material will reach 5,000 cubic yards in 1960 and increase at a rate of approximately twenty percent per decade thereafter.

In 1956, the Department of Sanitary Engineering and Water Resources, The Johns Hopkins University, made a search within a 125-mile radius of Erie, Pennsylvania, to discover a possible site for a

nationa; burial ground to serve a sixteen state section of the United States, an area generally east of the Mississippi River and north of the Potomac River. Forty potential sites were visited and eleven were finally chosen as possible burial ground locations. The eleven sites were rated on the basis of unit transportation cost from their major waste producers, site availability, topography, surface water hydrology, soil conditions, ease in excavation of the overburden, adequate structures, 100-year burial capacity, population density, incineration feasibility and rail-siding and highway availability.

The report was submitted to the Division of Reactor Development, A.E.C. Several staff sessions were held at Commission headquarters with interested Divisions represented, and a staff paper was prepared for circulation to the several Divisions. A decision from the Commission is awaited to implement or deny the establishment of a national burial ground to serve the northeastern section of this country.

Feasibility of establishing a national burial ground for radioactive wastes in the Northeastern United States, distributed by the Washington Atomic Energy Commission office.

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* Title 10, Atomic Energy, Chapter 1, Atomic Energy Commission, Part 20, "Standards for Protection Against Radiation," Federal Register, Volume 22, Number 19, 29 January 1957, Washington, D. C.

Group V. Item 2.

An Operations Research Study of the Transportation of Highly Radioactive Materials

It is the general purpose of this project to study the various methods available for transporting highly radioactive materials, using the techniques of operations research, to develop an acceptable basis for the decisions and policies required in the control of such shipments.

The project was begun in November of 1957 with a small research team consisting of Professor J. T. Thompson and Mr. F. F. Leimkuhler, with consultation from Professor E. Naddor, all of The Johns Hopkins University. An extensive survey was made of the existing knowledge and opinion in the field, on the basis of which the following research program was established:

1. Translation of the operational problem into a research problem with clearly defined objectives and a satisfactory measure of effectiveness.
2. Construction and solution of mathematical models which express the effectiveness of a transportation method as a function of a set of variable elements, at least one of which is subject to control.
3. Analysis and measurement of the significant variable and fixed elements of the transportation problem.
4. Testing the theoretical results against reality, and translation of results into decision-rules that can be applied successfully in the formulation of policies, regulations, and standards.

The research problem was initially formulated as one of cost minimization subject to a very limited number of variable factors. A mathematical model was developed and evaluated using hypothetical data in order to demonstrate its applicability to the problem area. This work was reported in a paper entitled, "An Operations Research Study of the Transportation of Highly Radioactive Materials," and presented at the Fourth Joint Military-Industry Packaging and Materials Handling Symposium, sponsored by the Office of Naval Materials, Department of the Navy, October 1, 1958, in Washington D. C. One hundred fifty copies of this paper were distributed to the A. E. C. and a number of other interested parties.

On the basis of the results of the initial model, a more detailed investigation has been undertaken in regard to what appears to be the most significant factors affecting the cost and safety of radioactive shipments, i.e. the design and integrity of containers, the frequency and severity of transportation accidents, radiation damages, and freight cost. In addition, work has been done towards improving the original model as regards its sensitivity and applicability. A plan has been developed to apply the revised model to a test situation, i.e. truck movement of radioactive materials through a large city.

This plan will be vigorously pursued in the immediate future with special emphasis on attempts to augment the present store of realistic numerical data.

A more detailed report of the present status of the project and of plans for the future is now being prepared for distribution to the A.E.C. at an early date.

AN OPERATIONS RESEARCH STUDY OF THE TRANSPORTATION OF HIGHLY RADIOACTIVE MATERIALS

Progress Report, April 1959

by

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ABSTRACT

The transportation of highly radioactive materials is treated as an operations research problem of selecting that combination of controllable transportation factors which minimizes cost and maximizes safety. Maximum safety is equated with minimum expected hazard cost, which makes it possible to construct decision models in terms of a total transportation cost, including the expected hazard cost. A detailed analysis is made of the significant factors in the transportation problem; and various methods of evaluating transportation hazards are examined. Examples and applications of the decision models are presented in considerable detail.

I. INTRODUCTION

A. Purpose and Scope of the Project

It is the general purpose of this project to make a systematic evaluation of the various alternative methods available in the transportation of highly radioactive materials, using the techniques of operations research to determine those methods which optimize both the cost and the safety of transportation. Such an analysis will make a substantial contribution to the development of a realistic basis for the policies and decisions required in the regulation and control of such activities.

The project was begun in November 1957 with a small research team consisting of Professor J. T. Thompson and Mr. F. F. Leimkuhler, with consultation from Professor E. Naddor, all of The Johns Hopkins University, Baltimore, Maryland. An extensive survey was made of the existing knowledge and opinion in the field, on the basis of which the following research program was established:

1. Translation of the operational problem into a research problem with clearly defined objectives and criteria for the evaluation of alternative methods of transportation.

2. Analysis of significant factors in the transportation problem, and the identification of alternative methods which are available.

3. Construction and solution of mathematical models which evaluate the total effectiveness of the various alternatives, and establish the conditions for maximum safety and minimum cost.

4. Reconciliation of theoretical results with reality, and the translation of results into decision-rules that can be used in the formulation of policies, standards, and regulations.

B. Progress Summary

The research problem has been initially formulated as one of minimizing the total cost of transportation which includes the expected hazard cost as a measure of the safety criteria. A mathematical model was developed early in the study and evaluated for long distance shipments of highly radioactive liquids, using hypothetical data, in order to demonstrate its applicability to the problem area. This work was reported in a paper which was presented at the Fourth Jount Military-Industry Packaging Symposium, sponsored by the Office of Naval Materials, Department of the Navy, October 1, 1958 in Washington, D. C. Approximately one hundred and fifty copies of this paper were distributed to the A.E.C. and a number of other interested parties.

On the basis of the results of the initial model, a more detailed investigation was undertaken in regard to what appears to be the more significant factors affecting the cost and safety of radioactive shipments, i.e. the nature and amount of the material, the design and integrity of the container, the mode of transportation and the vehicle, the selection of routes, and the use of such security measures as escorts, communication systems, and inspection procedures. In addition, work has been done on improving the original model with regard to the measurement of cost criteria and especially the estimation of expected hazard cost. Work has started on the development of a special detailed model for the evaluation of truck shipments of irradiated fuel elements through metropolitan areas.

Sources of hazard data have been discovered and cooperative arrangements made for their use. The data consist of transportation accident reports in the files of I.C.C.; research data on the severity and frequency of accidents and on freight costs developed by the Bureau of Public Roads in cooperation with some of the states; data compiled by insurance groups on the premiums charged for a wide range of risks in the transportation of extra hazardous products including nuclear materials, which data, it is hoped, may be used as a measure of hazard costs; and detailed route information concerning highways through and around the metropolitan area chosen for study, including complete data on the highways themselves and their traffic, as well as on the environment through which they pass.

Additionally, contacts have been made with a number of agencies both in the government and among private sources which possess the facilities and personnel to undertake a series of tests in which models of containers for shipping nuclear materials may be subjected to simulated transportational accidents in an attempt to evaluate the resistance of these containers to release of their contents and to establish a set of badly needed criteria for their future design. It is hoped that these tests may be undertaken in the near future.

II. FORMULATION OF THE RESEARCH PROBLEM

The development of atomic energy, especially for power purposes, will require the transportation of substantial quantities of highly radioactive materials for such operations as reactor refueling, fuel processing, and waste disposal. Because a unique hazard exists wherever radioactivity is present, a major consideration is the adequate protection of the human environment from the dangers of exposure and contamination during normal operations and in the event of unforeseen accidents. In existing atomic facilities, detailed studies of the specific hazards have led to the development of protective measures, which in effect have minimized most of the danger. Such protective measures, however, can be very costly depending on the degree of safety required. The commercial considerations of a competitive nuclear economy make it necessary to re-examine existing controls and devise new ones in order to find acceptable ways of avoiding the high cost of excess safety, without unduly endangering life and property. Furthermore, the construction of large nuclear power plants near urban centers, as well as the development of mobile propulsion reactors for ships and aircraft, and the accompanying need to transport reactor by-products over public transport lanes, greatly magnifies the problem of nuclear hazards with regard to public safety. The fundamental problem in transportation is basically the same as that confronting the entire nuclear industry, that is, the need to determine in advance the optimum balance between the risks involved the the protection required.

A. Alternatives and Controllable Factors

The purpose of this study is to make a systematic evaluation of the various alternative methods available in the transportation of highly radioactive materials using the methods of operations research. In operations research the system under study is usually represented by a mathematical model. Models are used to find the effect of the various alternatives on some stated objective, which is to be maximized (or minimized). Thus, the solution of the operations research problem eventually helps in making decisions or formulating policies. For a meaningful problem to exist there must be more than one way to perform the operation. If there is only one way, there is no problem. On the other hand, the various alternatives which are available may be so large that it is impractical or technically impossible to consider them all. In this case, the decision problem may be to find the best alternative from a limited set of alternatives.

Alternatives are described in terms of the controllable factors in the operation. It is possible to identify five major factors in the transportation of radioactive materials: (1) the nature and amount of the radioactive material shipped, (2) the design and construction of the container used in the shipment, (3) the mode of transportation used and the design of the vehicle, (4) the route selected for the shipment, and finally (5) the security measures or escort provided for the shipment. All five of these factors are subject to some degree of control. For example, the material can be modified by longer "cooling" prior to shipment or by making more shipments with smaller amounts per shipment. Containers can be

modified by using heavier structural members and by using special mountings for the absorption of shocks. Different modes of transportation are available to most locations with option of using special type vehicles. Routing can be varied as regards such factors as bypasses, and speed of travel. Finally, there are various security measures that can be used such as escort personnel, escort or buffer vehicles, communication systems, and enroute inspections. If for each of these five factors there existed just two possibilities each, then there would exist $2^5 = 32$ alternatives to be evaluated.

B. Criteria for the Evaluation of Alternatives

Alternatives are evaluated according to two kinds of criteria: restrictive and optimizing criteria. Restrictive criteria are the limitations inherent in the operation or imposed upon it. For example, with regard to the criticality of fissionable materials, basic safety rules have been developed and published which limit the container capacity, shipment quantity, and storage array of fissionable materials. Other restrictive criteria in the transportation of radioactive materials include such items as the permissible radioactive dose-rate at the surface of a container, dose limitation for humans, permissible concentrations of radioactive substances in the human environment, limitations on the gross weight of container handling equipment and on vehicles, and the availability of alternate rail or truck routes. Any alternative method of shipment which satisfies the restrictive criteria is a feasible alternative and a possible solution to the problem. Otherwise, the alternative is non-feasible and is eliminated from the feasible set under consideration.

The second kind of criteria to be applied to the remaining feasible set of alternatives consists in those measures which are to be maximized or minimized. In general, two such criteria are important in the transportation of radioactive materials: economy and safety. Accordingly, the transportation costs are to be minimized and the safety is to be maximized. Included in the cost of transportation are such items as the cost of preparation and packaging of the material. Preparations costs may be expressed as a certain dollar cost per shipment; and packaging costs may be expressed in terms of the total cost of the container and its maintenance pro-rated over its useful life, expressed in mileage or hours of use, i.e. a package cost rate in dollars per mile or dollars per hour. Other cost items include freight cost and escort cost, both of which involve the use of labor, equipment, and materials (such as fuel, tires, etc.) and are expressable in terms of cost rates per mile or per hour. In this way, the cost criteria can take the form of minimizing the number of shipments, the number of miles, and the number of hours involved in the transportation activity considered, each of which can be converted to dollar costs by applying the respective rates.

The second optimizing criteria to be applied to the alternative methods of transportation is that of safety. Any measurement of the safety of hazardous operations must take into account both the kinds of hazardous events which can occur and their frequency of occurrence. Industrial hazards are usually classified according to their causes (e.g. equipment failure, human, weather, etc.) and their effects (e.g. fatal, injury, property damage). A safety criterion can be

established for each, i.e minimize the frequency of equipment failures, fatal accidents, etc., but this can yield a large number of overlapping criteria. The frequency of hazards, classified according to their effects, can be expressed in terms of their causes by knowing the conditional probability that each effect will result from each of the causes. Thus the frequency of fatal accidents equals the sum of the products of the frequencies of each of the causes times the conditional probability that the cause will result in a fatal accident. In this way, a safety criterion would be the minimization of the frequency of fatal accidents, for example, which can be accomplished by reducing the frequency of the causes or changing the conditional probabilities, or both. However, there will still be as many criteria as there are hazard consequences to be minimized. In order to derive a single safety criterion, it is necessary to use a common measure of the severity of the different hazard consequences.

The most general method of measuring the consequences of hazards for economic purposes is to convert the consequences into dollar costs. This corresponds to the methods used by insurance companies where the expected dollar losses is used as the basis for setting premiums on policies. The use of an expected hazard cost as the safety criterion in transportation of radioactive materials has another desirable feature: it is compatible with the other cost criteria developed previously. In order to determine the best possible alternative, it is necessary to have a common measure of the total effectiveness when all criteria are considered. The relationship which expresses the total effectiveness of a system as a function of the alternatives or the controllable factors is the general model of the system.

C. Mathematical Models

The total cost for a given alternative method of transporting radioactive materials, in terms of the criteria developed above, can be determined from the following general model:

$$T(A) = P(A) + F(A) + S(A) + H(A)$$

where: $T(A)$ = the total transportation cost for alternative A, $P(A)$ = the packaging cost, $F(A)$ = the freight cost, $S(A)$ = the security cost and $H(A)$ = the expected hazard cost associated with the given alternative. Each alternative is a feasible combination of the controllable factors, denoted by: M = materials, C = container, V = vehicle, R = route, and E = escort provisions. Thus, in functional notation an alternative is expressed as a vector: Alternative $A_i = (M_f, C_g, V_h, R_j, E_k)$ where the subscripts refer to specific choices of the controllable factors, e.g. $A_5 = (M_2C_3V_2R_1E_2)$.

A preliminary analysis of each of the controllable factors has been made in order to identify meaningful transportation alternatives and to measure their contribution to the cost criteria. The results of this analysis are reported in Part III of this report. Of particular significance is the measurement of the hazard cost criteria. Since there is almost no experience on which to base statistical measures of the frequency of radioactive hazards and the cost consequences of such hazards, analytic methods are required. Some studies of the evaluation of hazards are reported in Part IV of the report. The lack of sufficient information about many of the factors has made it necessary initially to restrict attention to limited versions of the general model. In order to demonstrate the

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evaluation of such models and their applicability to the problem area, hypothetical data has been used to evaluate certain specific applications of the general model. The results of this work are reported in Part V of the report.

As an example of the evaluation and application of a single-factor model, consider the problem of minimizing the total cost of transportation between two points where the alternatives are simply the different routes between the two points, and the total cost for any one route can be expressed as:

$$T(R_i) = \sum_j c_j m_{ij}(R_i)$$

where route "R_i" is composed of a certain number of each of the type "j" miles, denoted "m_{ij}"; and corresponding to each mileage type there is a cost rate "c_j" ($j = 1,2,\ldots,n$). Thus the shortest route, R_o, is composed of $m_{o1} + m_{o2} + \ldots + m_{on}$ miles; and the total cost is given by

$$T(R_o) = \sum_j c_j m_{oj} \quad \text{where } \sum_j m_{oj} \leq \sum_j m_{ij}(R_i) \text{ for } (i \neq o).$$

Now consider the special case where there is no difference in cost rate between miles and the cost rates "c_j" are all the same and equal to a constant "c", then

$$T(R_i) = c \sum_j m_{ij}(R_i) \geq c \sum_j m_{oj} \quad \text{for } (i \neq o)$$

That is, the shortest route is also the minimum cost route. If the cost rates are not equal to a constant, then it can be shown, in general, that a longer route can exist which yields a smaller total cost, by merely reducing the more expensive miles and increasing the less expensive miles up to the ratio of their cost rates. Thus the larger the cost ratio between two different mileage types, the larger

the substitution that can be made. For example, if the cost ratio between city miles and rural miles is 10 to 1, and the shortest route between two points is composed of 20 rural miles and 5 city miles, then an alternative route composed of 70 rural miles and no urban miles would have exactly the same transportation cost. These results serve to indicate the relative importance of considering route selection as a significant factor in the transportation problem. Only if there is a relatively constant cost per mile for all route miles, does the route selection problem reduce to the simpler solution of choosing the shortest route.

III. ANALYSIS OF SIGNIFICANT FACTORS

A. Survey of Shipments of Highly Radioactive Materials

A survey of the shipping practices of the various A.E.C. Operations Offices was made in 1956-1957 under the auspices of the A.E.C.'s ad hoc Committee on the Transportation of Highly Radioactive Materials. Types of containers, materials shipped, carriers, and other related information was collected and presented in an unpublished reportby Mr. Arnold Joseph. This information was made available to the project, and a preliminary study was made of these data in order to identify certain general characteristics of a repetitive nature. The data studied appeared to indicate a relationship between container weight and curie content, such that as the weight doubled, the curie load increased by a factor of ten, indicating the relative weight advantage of shipping larger quantities of radioactive material. It was suggested that the shipments reported could be classified into certain broad divisions, as follows: (a) isotope shipments in small quantities (less than 1 curie) in containers of less than approximately 300 lbs.; (b) research shipments of medium size (1 to 10,000 curies) in containers ranging from 300 to 7500 lbs.; and (c) production shipments in large quantities (up to 10^7 curies) in containers ranging from 14,000 lbs. to 70 tons.

It was decided to focus attention on the production type shipments for the immediate purposes of the project; and in particular, to consider two specific types of shipments in this category. They were: (a) shipment of irradiated MTR fuel elements from the reactor site at Idaho Falls, Idaho, in one or more of the recently designed containers for this purpose, and (b) shipments of fission product solutions, similar to

those being made on pilot plant scale between Idaho Falls and Oak Ridge. The latter shipment was considered for the hypothetical evaluation developed early in the project and reported below. However, it was decided to concentrate subsequent and more detailed analysis on shipments of the MTR fuel elements, since these shipments are similar to those required in the refueling of power reactors using solid fuel elements.

1. Notes on MTR Fuel Elements (from selected references)

The Materials Testing Reactor (MTR) was completed in 1952 for the primary purpose of studying the effects of nuclear radiations on materials required for reactor construction. It was designed, therefore, to provide a higher neutron flux than any existing reactor, and employs solid highly enriched uranium fuel elements with ordinary water as moderator. The core of the MTR contains only about 4 kg of Uranium-235 but with forced convection cooling the reactor operates at 30,000 kw (heat). The average thermal neutron flux is 2×10^{14} neutrons/(cm^2)(sec.). The thermal shield consists of two 4 in. layers of steel (air cooled) and the biological shield consists of 9 ft. of barytes concrete on the sides and 17-1/2 ft. of water on the top.

The box-like fuel elements (or assemblies) of the MTR consists of 18 thin curved fuel-bearing plates, each of which is approximately 2.8 in. wide and 2 ft. long. Each plate is a sandwich affair with a 0.02 in. thick layer of an aluminum alloy with 10 to 20% by weight of highly enriched uranium (approximately 93% U-235) clad on each side with aluminum of the same thickness to prevent escape of the fission products and corrosion of the alloy. These plates are assembled 0.12 in. apart and brazed into aluminum side-members to form a completed assembly of roughly 3 x 3 in. across.

In loading the reactor the new fuel assemblies are lowered into place by hand from the top of the reactor. The bottom of each assembly fits into a socket in the grid base of the reactor core, while another grid fits over the top thus holding the units in place. There are some 20 assemblies in the loaded reactor, located in a space of roughly 15 x 17 in. cross-section. The mass of Uranium-235 in each assembly is approximately 200 grams. The reactor is unloaded with manually operated grappling tools through almost 20 ft. of water. The spent fuel element is lifted just above the beryllium reflector and moved horizontally to a position over a hole that is normally filled with a beryllium plug. The fuel assembly is then lowered into a water-filled discharge tube from which it is transferred by a special unloading device into a canal containing an 18 ft. depth of water.

The Atomic Energy Commission makes irradiated reactor fuel elements available for use by industry and research institutions as gamma-ray sources. Users must obtain special nuclear material and by-product material licenses. A spent fuel element from the MTR (after cooling 90 days) has a gamma radiation rate of approximately 200,000 roentgens per hour as measured by an ion chamber through 3 in. of water from the fuel element at mid-plane. The elements with end boxes removed are about 24 in. long and 3 x 3 in. in cross-section. The charge for use of a MTR fuel element is $100 per year, or a fraction thereof, plus handling charges. The handling charge is estimated to be $225 for each shipment and an additional $225 upon return of a cask. Handling charges may be less for truck shipments. Transportation costs are borne by the user.

In the shipping data for the year 1955-56 (presented above) six shipments of MTR fuel elements were made from Idaho Falls to the Argonne National Laboratory in Chicago. The ANL container used for these shipments is known as the "Gamma Irradiation Facility Carrier" (Bureau of Explosives Permit No. 200). It is designed to carry four irradiated MTR fuel elements at one time in a stainless steel compartmented cylinder of 8-1/2 in. diameter and 26 in. height. This is surrounded with a 12 in. lead shield, and the shielded container is further enclosed in a stainless steel outside tank with 96 vertical fins around it. Between the shield and the outside wall and within the inner compartment 180 gallons of water are allowed to circulate. The overall dimensions of the container are 48 in. in diameter and 73 in. in height, providing a total shield effect of 12 in. of lead, 1-1/8 in. of iron, and 4 in. of water. By computing the relationship $I_o = I \exp(\mu p)$, where I is the permissible outside surface radiation (200 mr/hr) and (μt) is the attenuation and thickness of the shield, it is possible to rate the radiation capacity of the container for the source, I_o, at 3×10^{10} roentgens/hr. The total weight of the container is 24,520 lbs. (shipping weight 26,500 lbs.). It was fabricated at a cost of $18,300. The reported curie contents for the six shipments in the above data were: 4, 10, 10, 1, 6 and 1×10^5 curies. Typical shipping costs for one container of four elements from the Idaho Operations Office to the Argonne National Laboratory (and return of empty cask) are shown in an A.E.C. report AECU-3254. The total costs are:

Total Freight Cost	$1648.89
Total Escort Cost	1242.75
Transportation Cost	$2891.64

2. Remarks on Mixed Fission Product Shipments

The major waste disposal problem arising from reactor operations is associated with the fission products in the irradiated fuels. Fission products separated from spent fuel elements at a chemical processing plant usually are mixed with cladding materials and waste chemical reagents of the processing. The volume of wastes for disposal depends on the characteristics of the fuel and the type of process to be used. Current methods produce from 0.5 to 5 gallons per gram of uranium processed. The radioactivity levels vary over a range from 150 to 1500 curies per gallon of waste.

To date, storage of high level concentrates in tanks has been safe and adequate, but tank storage is not an ultimate waste disposal method because of the relatively short useful life of tanks as compared with the long term (hundreds of years) hazards of the fission product wastes. Several promising approaches to ultimate safe disposal of high level wastes are the subject of current research by the A.E.C. Cesium-137 and Strontium-90, because of their very long half-lives, are the most troublesome fission products. The next long-lived element has a half-life of less than 1/30 of either of the first two. After 10 years of storage, essentially all of the gamma activity comes from Cesium and most of the beta activity comes from Strontium. Research toward the economic removal of Cesium and Strontium is currently being conducted. The first plant for the large scale production of the radioisotopes from spent fuels is being built at Oak Ridge.

By July, 1956, two shipments had been made of fission product wastes from Idaho Falls to Oak Ridge (over 2500 miles) in a specially constructed container for that purpose. Five thousand curies of waste were carried and radiation measurements outside the tank indicated that 50 times as much could be carried safely. The container used is known as the "Shielded Transfer Tank," STT, and is essentially a stainless steel, spherical, 250 gal. container of 48 in. inside diameter, enclosed with 5-1/2 in. of lead shielding. The outside cladding is of 13/16 in. steel plate, stainless on the outside to provide protection against external forces and internal pressures in case of fire or accident. It is mounted on a steel skid 84 in. square. The outside diameter of the sphere is 61-5/8 in., and the total empty weight (including skid) is 28,200 lbs. Only one container was fabricated for Oak Ridge by Lukens Steel at a cost of $22,726 plus engineering costs of $2,500. The radiation capacity of the STT is estimated at 6×10^4 r/hr. In the two shipments mentioned above the mode was by rail freight (UP-MD-Sou), and the reported costs were $1,101.00 shipping cost, $1,309.00 courier cost, and $150.00 unidentified (FPCo.) for each shipment.

Oak Ridge National Laboratory is preparing to institute a fairly regular long haul movement of high level liquid wastes from Arco to Oak Ridge. The material will be shipped in 38,000 lbs. cylindrical containers holding 500 gals. each. Three containers will be shipped at one time in a railroad gondola car. (ORNL is paying for a minimum weight of 115,000 lbs. per shipment (150,000 lb. max) at a rate of $2.12 per cwt for the loaded containers and $1.06 per cwt for the empty containers on the backhaul.) Total cost for

a roundtrip will be about $3500. The cars are equipped with a special base for bolting down the containers. The containers have an inside shell of 3/8" stainless steel, a 3-1/2" lead shield, and an outside shell of 1" steel plate. The outside shell is surrounded with steel fins to aid in cooling and to add rigidity to the construction. To prevent leakage there are no vapor escape valves. This container will carry Redox wastes.

B. Container Design and Behavior

The total cost equation which we are attempting to minimize has two terms which require knowledge, not now available, of the behavior of containers in the event of a transportation accident. One of these terms is the cost of the container itself. It is suspected that shipping casks now in use are heavily overdesigned and the minimization of cost is influenced by the degree to which less costly design may be accomplished. Associated with this element of minimization is, presumably, the increase in expected hazard cost, i.e. the lighter the design and construction, the greater the chance of escape of radioactive, toxic, materials into the environment. It should also be noted, incidentally, that the weight of the container influences another term of the equation, namely freight cost.

The approach to the total cost minimization problem as we have conceived it requires, ideally, that we be able to say with usable accuracy what degree of release is likely to occur for designs of varying strength following accidents of varying degrees of seriousness. As one can easily see this is a task of extreme

difficulty and it is our judgment that it will require the organization of the best analytical talent procurable in the fields of energy dynamics and limit design coupled with an extensive program of model or perhaps full-size tests. Such a combination of analytical and test programs will be time consuming and very costly but the rewards in the direction of safety, economy, and standardization of containers and procedures generally will be immense.

We believe that the scope and magnitude of such an undertaking are far beyond the capacities of our project. Our role in this connection would be to advise, to observe, and above all to make sure that the results as they are being developed are consistent with the needs of the project so that ultimately a solution to the whole transportation problem, transcending that of container design alone, would be forthcoming.

Meanwhile we will proceed with what analytical applications we may be able to devise and procure with our limited resources, hoping to acquire some gross estimates associated with container design. In addition, we will continue to seek information which may serve both as a basis for decision by A.E.C. and as a stock-pile of availabilities which may be quickly applied should the decision be to proceed with a program of analytical work and testing.

Accordingly, aside from collecting data on transportation accidents per se, we have established a number of contacts with agencies and individuals who either have data, "know-how," or access to testing facilities, or who are proving useful to the project in one way or another. A brief summary of these contacts is set forth below.

Conferences have been held with staff of the following organizations. In some instances testing facilities were examined, and in every instance information and ideas of value to the project were forthcoming:

Library, Dept. Commerce, U.S. Bureau Public Roads, Washington, D.C
Naval Experiment Station, Annapolis, Maryland
Ordnance Dept., Aberdeen, Maryland
Chemical Warfare Center, Edgewood Arsenal, Maryland
Biological Warfare Center, Fort Detrick, Frederick, Maryland
Glenn L. Martin Co., Middle River, Maryland
Union Carbide Co., Oak Ridge, Tennessee
du Pont Co., Wilmington, Delaware
Mosler Safe Co., Hamilton, Ohio
Bureau of Explosives, New York
Southwestern Research Laboratory, San Antonio, Texas
Broadview Research Corp., Burlingame, California

Contacts have been established and correspondence is being exchanged between the project and the following. Valuable suggestions are being received:

Underwater Explosives Research Division, U. S. Navy, Portsmouth Va
Naval Ordnance Laboratory, White Oak, Maryland
U. S. Army Signal Research Laboratory, Fort Monmouth, N. J.
Q. M. Research & Engineering Command, U.S. Army, Chicago, Ill.
Armour Research Foundation, Illinois Inst. Tech., Chicago, Ill.
Association American Railroads, Research Center, Chicago, Ill.

Additionally, the following items, which do not seem to fit into either of the above categories of contacts, are worthy of recording:

Messrs. Leimkuhler and Thompson attended the 4th Annual Military-Industry Packaging and Materials Handling Symposium in Washington, D. C., Oct. 1, 1958, where they presented a paper entitled, "An Operations Research Study of the Transportation of Highly Radioactive Materials." This paper was in effect the first progress report from the project. They also attended a meeting of the A.E.C. ad hoc Committee on the Transportation of Highly Radioactive Materials. Further contacts were established here between the project and representatives of A.E.C. contractors from General Electric and Phillips Petroleum who are particularly interested in containers.

Additionally, they conferred with Dr. C. R. McCullough of A.E.C. regarding the relationship of container design and hazard cost.

Mr. Thompson has recently been appointed a member of Sub-Committee N5-5 of the American Standards Association. This sub-committee, whose interest is in the packaging and transportation of radioactive materials, held its first meeting in New York on January 29, 1959.

Dr. Frederick Seitz, of the University of Illinois, has given the project valuable advice regarding the effect of radiation on materials used in container design.

C. Transportation Mode and Procedures

The transportation mode and related shipping procedures can play an important role in the costs and hazards of radioactive shipments. Included in this category are such variable items as the selection of the mode (rail, truck, air, etc.), vehicle, route, speed of operation, escort vehicles and personnel, weather conditions and time of day, position in train, en route inspections, and communication systems. The basic freight cost alone can be very significant because of the weight and size of shielded containers. This is especially significant with regard to the high cost of back-shipping empty containers, since the dead weight may be 95% or more of the loaded weight. The contribution to hazards lies mainly in the fact that transportation accidents are the most significant cause to be considered in determining the possibility of container failure and accidental release of radioactive materials.

1. Selection of Mode of Transportation and Vehicle

In practice, the container appears to be a major determinant of the transportation mode and vehicle used. The general geometry of the container shielding problem is such that shield weight per unit volume of radioactive load falls off rapidly as the size of the container is increased. Studies at Oak Ridge indicate the possibility of making significant reductions in shield weight through the use of spent uranium as a shield material, but the geometry will remain the same. The tendency to use larger containers is clearly evident in the shipping container data collected by the A.E.C. and made available to the project. Container weights currently in use appear to be distributed in such a manner that they center about the acceptable weight limits for various transportation modes and vehicles.

Another important factor influencing the tendency to standardize container weights is the standardization of container handling facilities at such installations as fuel re-processing plants. In general, therefore, it seems reasonable to anticipate that the routine shipments of highly radioactive materials in the foreseeable future will be made largely by railroad and truck in full carload and truckload amounts. In shipping by railroad there is evidence that both single-unit and multi-unit carloading methods may be used. A single unit container fully occupies the railroad car and weighs in the order of 70 tons. In multi-unit shipments the carload is composed of several smaller containers, perhaps in the order of 15 to 20 tons each. In the latter case, there is a loss in packaging efficiency, which is compensated for by the advantage in being able to move the smaller packages by truck to and from railroad sidings and within plant sites.

For the purposes of this project it was decided to focus attention on containers of the 15 ton class, i.e. truckload size, and on highway shipment of such containers using 5-axle tractor-trailer combination vehicles. It is believed that this specification of the mode, vehicle, and container will be sufficiently general for wide application. Methods developed in its evaluation should prove useful in extending the investigation to railroad shipments of the multi-unit and single-unit type, as well as variations in truck shipments.

2. Selection of Routes and Special Shipping Procedures

Of the many variable factors involved in radioactive shipments, those associated with the manner of operation of the transportation vehicle appear to be most readily subject to the control of the

shipper, since in most instances the material, container, and mode of transport have been specified beforehand and lie outside the control of the shipper. The shipper is more likely to be in a position to select the route; establish special procedures for speed, time of day, weather conditions and communications; and provide for escort vehicles and personnel, special monitoring equipment, and en route inspections.

Route selection was chosen to be the first such control variable to be evaluated for answers to these questions, and the larger question of finding the overall optimum method of shipping. Between a given origin and destination, there exists only a limited number of regular truck routes suitable for tractor-trailer combinations and a much more limited number of rail routes, but it is possible that even small variations in regular routes such as the use of bypasses to avoid urban centers, tunnels, bridges, etc., might make a significant contribution to the overall safety of the shipment. In order to determine this contribution and the accompanying variation in cost, it is necessary to define the route in terms of the number of different kinds of cost miles and hazard miles. The study of freight costs, reported below, indicates that speed of travel might be a sufficient indicator of the freight cost associated with each route mile. If this simple technique proves acceptable in the course of further study, it will only be necessary to determine the number of miles that are rated for different speeds in order to estimate the freight cost for a given route, and thereby determine the relative cost advantage of different routes in terms of freight or other similar cost parameters.

The determination of the relative advantages of different routes with regard to the nuclear hazard is proving to be a much more difficult problem, as might be expected. The studies of nuclear accidents reported elsewhere indicate that the location of the shipment at any given time will affect at least three important considerations in the hazard problem. The first of these is the probability of the shipment being involved in an accident; the second is the severity of the accident, and the third is the radiation damages that will result from exposure and contamination as a result of container failure in the event of an accident. Truck accident statistics indicate a significant difference between the frequency and severity of accidents occurring under different road conditions. For example, rural accidents are generally less frequent but more severe. On the other hand, analytical studies of the consequences of nuclear accidents place great importance on the population, terrain, weather conditions, proximity of emergency crews, etc., all of which can be considered as measurable features of the route. That route which offers the best overall combination of these features is naturally the one to select. A hypothetical example of route selection using some of the above criteria is presented later in the report. It is because the "route selection" problem brings so many basic features of the more general transportation problem into play, that it has been deemed worthwhile to explore this problem extensively. Solutions to this problem should find wide applicability in solving more general aspects of the problem.

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The employment of the other control variables mentioned above such as speed control, escorts, communications, and en route inspections appear to lead to the same kind of evaluation problems as those involved in the selection of the route. Only limited attention has been given to these control possibilities because of the lack of available manpower and the relative importance of other features of the problem. A hypothetical example of the utilization of escorts is presented later in the report in conjunction with a hypothetical route and container selection example.

3. Determination of Freight Costs

An investigation is being made to determine reliable estimates of the costs associated with full truckload shipments in 5-axle tractor-trailer combinations. Valuable initial guidance was given by the U.S. Bureau of Public Roads, where recent, extensive, and reliable cost studies of this type are being made in cooperation with several of the States. Available data were collected along with other references, and an attempt has been made to extract suitable cost estimates and their variation under different road conditions.

The State of California Public Utilities Commission has proven to be the best source of information on this topic to date. The Transportation Division of the Commission maintains an engineering staff which makes extensive cost studies for the purpose of establishing freight rates in the State of California. These costs are designed to reflect the operations of carriers operating in a typical manner under present service demands and economic conditions. In general,

the total cost is expressed as the sum of such component costs as: equipment, fixed cost prorated over time or distance, running cost per mile, labor cost, and indirect cost expressed as a percentage of direct cost. In order to account for the variation in cost due to road conditions, the cost data are reduced to estimated average total cost per mile for the vehicle operating on a flat, rural road at an average speed of 35 mph. This constitutes a minimum or standard cost, expressed as the cost per standard or "constructive" mile. Two major factors have been identified which tend to increase the cost per mile. These are (a) rise and fall of the road, and (b) urban developments which contribute delays and reduced speeds. The effect of these two factors on freight cost have been determined as a percentage increase in cost for a given road grade or degree of urbanization. As a convenience in determining the total trip cost for a particular route, the actual route miles are converted to constructive miles by applying the percentages mentioned above to the mileage breakdown of the route. In the State of California, all truck route distances have been converted to constructive mileage distances by actually physically surveying the road conditions. This results in a very efficient technique for establishing estimates for freight rates.

For the purposes of this project it was decided to use as much of the California data as possible in estimating freight costs parameters, since we have been assured from other sources that the data is as reliable as any available. As a result the following component freight costs were estimated.

Table 1. Estimated Freight Costs for Truckload Shipments by 3 Axle Tractor-2 Axle Van Combinations 2/

Item	3-Axle Tractor	2-Axle Van Semitrailer	Combination Unit
Service Cost (historic cost less salvage value)	$ 12,700	$ 6,050	$ 18,750
Service Life in years	10	12	-
Depreciation per year	1,270	504	1,774
Annual Licenses and Fees	388	157	545
Fixed Annual Costs	1,658	661	2,319
Annual Longhaul Usage (hours/year)	3,200	3,000	-
Depreciation and License Cost/hr.	0.518	0.220	0.738
Labor Cost per hour (1 driver)			2.930
Total Hourly Cost			3.668
Fuel and Oil Cost per mile	0.046		0.046
Tire Cost per mile	0.012	0.009	0.021
Maintenance Cost per mile	0.058	0.013	0.071
Total Running Cost per mile	$ 0.116	$0.022	$ 0.138
Overhead as a % of Direct Cost			0.140
Special Fees as % of Direct Cost			0.048
Profit as a % of Direct Cost			0.110
Total Indirect Cost as a % of Direct Cost			$ 0.338

Using the data shown in Table 1, an elementary expression for freight cost per mile is derived as follows:

$$\text{Freight Cost} = (1 + I)(R + H/S)$$

where: I - indirect cost as a percentage of direct cost, R = running cost per mile, H = hourly cost per hour, and S = speed in miles per hour. In terms of the cost data in Table 1, this equation reduces to:

$$\text{Freight Cost (\$/mi.)} = 1.338(0.138 + 3.668/\text{Speed})$$

As indicated above, corrections are usually made in freight cost estimates to compensate for the variation in road conditions especially with regard to the rise and fall of the road and the degree of urbanization. A research study published by the Highway Research Board on this subject was used to derive estimates of the effects of highway conditions on freight costs. The published results are expressed as a function of the weight and power of the vehicle as well as the rise and fall in the highway. In order to derive typical, order of magnitude estimates for the present purposes of the project, the vehicle was assumed to have a gross weight of 60,000 lbs. and a weight/horsepower ratio of 400. Composite rise and fall values, i.e. where rise accounts for 45% to 55% of the total rise and fall, were used in all calculations. Two parameters, speed of travel and a fuel consumption or cost ratio, were extrapolated from the HRB report; and the following equation was used to determine freight cost:

$$\text{Freight Cost} = (1 + I)(f \times F + T + M + H/S)$$

where: I = indirect cost as a percentage of direct cost, f = fuel cost ratio, F = fuel cost/mile, T = tire cost/mile, M = maintenance cost/mile, H = hourly cost per hour, and S = speed in mile per hour. In terms of the cost data in Table 1, this equation reduces to:

$$\text{Freight Cost (\$/mi.)} = 1.338(0.046f + 0.092 + 3.668/\text{Speed})$$

The results of these calculations are shown in Table 2, next page.

Table 2. Estimated Freight Costs and Speeds Related to the Rate of Rise and Fall of the Road

Rate of Rise and Fall (ft/100 ft.)	Speed of Travel (mph)	Fuel Cost Ratio	Estimated Freight Cost ($/mile)
0.0	50	1.0	$0.284
1.0	45	1.2	0.306
1.3	40	1.3	0.327
1.7	35	1.4	0.349
2.3	30	1.6	0.385
3.0	25	1.8	0.431
3.8	20	2.1	0.498
5.0	15	2.4	0.598
7.0	10	4.0	0.860

No comparable studies of the effect of road urbanization on speed and freight costs have been found. In the absence of such studies, it has been tentatively decided to use the cost estimates of Table 2 for the purpose of costing both urban and rural miles, on a basis of the rated average speed for the miles in question. The cost estimates obtained in this way should be on the conservative side because of the weighting for increased fuel consumption as well as reduced speed due to the different average road grades. This weighting may serve to compensate for increased running costs due to stopping, starting, curves, and other cost factors on low speed roads. In the California studies referred to previously, compensation for urban development is taken care of by applying fixed cost ratios to urban miles. These ratios are arrived at by judgment rather than factual data. They apply a ratio of 1.18 to large city mileages and 1.10 to small city mileages.

It is believed that the methods of developing freight costs described above should prove adequate for the present purposes of the project. Actual shipping cost data obtained from various A.E.C.

installations exhibit an extremely wide variation due to the different methods used in establishing and reporting such costs. We have been advised by competent authorities that the most objective approach is the one taken, since the analysis of actual freight rates is a very uncertain business.

4. Evaluation of Accident Statistics

A study is being made of the available data concerning the frequency and severity of truck accidents. The principal sources being used are various reports and studies from the A.E.C., Interstate Commerce Commission, National Safety Council, Bureau of Public Roads, Highway Research Board, private and state agencies, and insurance companies. Work has begun on developing statistical procedures for evaluating this data in order to find reliable estimates and indicators of the expected frequency of truck accidents with reference to route location and road conditions; the expected consequences of such accidents as to driver injury, truck damage, and cargo damage; and the possible consequences such accidents would have on the container and radioactive materials, and on notification and emergency procedures for the protection, evacuation, and control of the human environment.

Accident frequency is usually reported on a per vehicle mile or per year basis with reference to the type of operation, vehicle, road, cargo, etc. Accident consequences are usually reported as to type of accident or collision, fatalities and injuries, and the cost of property damage and injury. The Interstate Commerce Commission compiles and publishes accident data on a regular quarterly basis from accident reports submitted by the carriers under their jurisdiction.

These data have been made available to the project, and give average frequency and severity rates by type of carrier and ICC motor carrier districts. The ICC has also indicated their willingness to make available more detailed statistics when the need arises. The National Safety Council publishes statistical summaries of accidents on an annual basis from data furnished by the various State agencies. This publication gives a more detailed breakdown of the data and covers a much wider class of vehicles than the ICC reports. Recently, there has been made available to the project the results of an extensive study of highway accidents sponsored jointly by the U. S. Bureau of Public Roads and the States of Massachusetts, New Mexico, and Illinois. This study promises to give highly reliable estimates and supporting statistical detail for the frequency and cost of truck accidents for a considerable number of breakdowns. Preliminary investigations of these data are being made at the present time. The distribution of accident costs for different vehicles, roads, and types of collisions appears to exhibit a log-normal type of distribution, on a basis of which it has been possible to make some test of significance between the means and variances of accident costs for different accident factors.

To date, no analytical studies of the dynamic aspects of truck accidents have been found. Such studies would be extremely valuable in predicting the accidental, structural loading on container and container mountings. In the absence of such data, it is planned to attempt to define certain indicators of the important dynamic aspects of an accident, where such indicators can be readily

identified from existing accident records. These indicators might include such items as speed, force value, and angle of impace, collision with fixed and moving objects, turn-over, fire, etc. By estimating the expected frequency of the indicators, it may be possible to translate them into measures of the expected container behavior and possible failure.

IV. EVALUATION OF HAZARDS

A. Insurance Rates as a Measure of Hazard Cost

One aspect of the public liability feature of the hazards problem is that of financial protection, which serves to give a measure of the order of magnitude of the problem. Extensive studies of this aspect of atomic hazards have concluded that despite every safety precaution taken, there exists the possibility of a catastrophic accident which could impose a crushing loss both on the public exposed to injury and on the enterprise operating or supplying the facility. The magnitude of the hazard is such that the potential liability cannot be covered by private insurance alone. Basically, it is this conclusion which led Congress in 1957 to enact the Price-Anderson Amendments to the Atomic Energy Act. The theory of this legislation is that the magnitude of the atomic hazard makes it necessary that the financial burden be shared between the industry taking the risk and the United States. This result has been accomplished by (a) requiring the industry to provide private financial protection for each facility but limiting the requirement to some amount under or equal to the maximum available depending on the facility (not likely to exceed $60,000,000), and (b) indemnifying the industry with public funds for any further liability imposed on it up to $500,000,000 per incident.

1. Nuclear Insurance Requirements

The Price-Anderson Amendments provide for determining the amount of financial protection required by consideration of such factors as (a) the cost and terms of private insurance, (b) the type, size, and location of the facility and other factors pertaining to

hazards, and (c) the nature and purpose of the licensed activity. In September of 1957 the Atomic Energy Commission issued a temporary regulation which provided the initial procedure for determining the amount of insurance required by licensed facilities. It was decided that an exact mathematical formula was unobtainable from existing knowledge, and a simple straight-line formula was developed whereby $150,000 of liability insurance is required for each thousand kilowatts of thermal capacity. A minimum of $250,000 per facility was also established. A great amount of consideration has been given to such factors as the type and design of a facility, its nature, and its purpose; but it is believed that there is insufficient data to furnish a meaningful differentiation in relative safety due to these factors.

A modification of the original formula is planned (or may be in effect) whereby the amount calculated above will be multiplied by a factor for location and a factor for fuel cycle. It is believed that the limiting factor on the size of a nuclear release is dependent primarily on the power level of the reactor and the length of time the fissionable material remains in the reactor. On the other hand, the extent of damage in potential liability is dependent on the location; and since location is considered to be the more important in respect to potential liability, there may be a greater spread in the location factor than in the fuel cycle factor. It is planned to use the population density in a reasonably sized area as the basis for the location factor, rather than land values since the latter information is not readily available for all locations. The power

level will be used to determine the radius of the area, for which the density will be computed. Special consideration may be given to nearby population centers.

2. The Cost of Nuclear Insurance

The private financial protection required under the Price-Anderson Amendments is being provided by two insurance pools organized by various insurance companies. The pools provide omnibus coverage of the nuclear energy hazard up to a specified aggregate liability limit per facility for bodily injury and property damage combined. They are prepared to make rate quotations on almost any nuclear exposure created by private industry within the United States, and have actually been writing insurance since March, 1957.

Because of the lack of sufficient experience, the rates quoted by the pool are subject to a credit rating plan applied over a moving ten year period to the experience of the nuclear energy industry as a whole. If it turns out that public liability losses from nuclear hazards are less than reserves, a portion of the surplus is returned to the policy holders after a period of time. The rates quoted are estimates of that share of the total nuclear industry risk that should be borne by the individual members of the industry, on a basis of their contribution to the overall risk. As such, therefore, the rates quoted give a relative measure of risk attaching to a particular nuclear facility being operated in the safest manner possible up to the limit of the technical knowledge available. Some representative quotations appearing in the literature are shown on next page.

Insurance Rates Quoted on Limited Nuclear Risks

Premiums per Year by Type of Nuclear Risk	Liability Limit/Incident $5 Million	$60 Million
Power Reactor - 630 mw thermal capacity	$ 120,000	$ 260,000
Power Reactor - 480 thermal capacity	60,000	140,000
Fuel Fabrication Plant	7,500	35,000
Critical Facility	6,000	33,500
Package Research Reactor	3,500	31,000

3. Liability Insurance for Transporters

Of particular interest to this project is a special policy for suppliers and transporters servicing nuclear facilities. Although such services are normally covered under the omnibus clause of the existing facility policies, there exists the possibility that such coverage in a particular instance may not be available. Therefore, a single interest policy is available to transporters and suppliers for coverage of their liability risk only, adjusted for the facility coverage in force and subject to the capacity of the pool. The Nuclear Energy Liability Insurance Association has been most cooperative in discussing the details of this policy with the project members and furnishing the rate schedule presently being applied to this type policy. The rates given below are typical of those applied to truck shipments of irradiated fuel elements. Shipments of new fuel elements are rated at 10% of the spent fuel rates, and shipments of low level waste materials are rated at 25% of the spent fuel rates.

Insurance Rates for Truck Shipments of Irradiated Fuel Elements

Max. Liability per Incident	Rate per Loaded Day	
$ 1,000,000	$ 25.00	
2,000,000	37.50	
3,000,000	50.00	
4,000,000	62.00	
5,000,000	75.00	
6,000,000	80.00	(Each additional
7,000,000	85.00	million over
8,000,000	90.00	10 million costs
9,000,000	95.00	$2.50 per day)
10,000,000	100.00	

In determining a premium, appropriate consideration is given to any coverage afforded to the named insured under the facility policy issued to the operator of the facility, for whom the nuclear materials are being transported. If the facility has available Price-Anderson indemnity, thus protecting the transporter, there would be no charge, since the transportation company first looks to the facility and government indemnity for coverage. All nuclear energy liability insurance rates are subject to any adjustments developed in accordance with the terms of the long-term industry-wide rating plan, which provides for a retroactive downward adjustment of premiums in the event that substantial losses do not emerge over a period of time and a surplus develops.

B. Analytical Methods of Hazard Evaluation

A survey has been made of the available analytical methods employed in the evaluation of nuclear hazards. Most of the published literature is concerned with the hazards associated with nuclear reactors. The emphasis is placed on evaluation of the most serious, credible accidents that can be envisioned, and this usually takes the form of a reactor explosion giving rise to nuclear cloud formation. Such accidents can result in a wide-spread release of fission products and contamination of the human environment. A study is being made of the nature and composition of irradiated MTR fuel elements in order to determine the possible types of radiation hazards and their consequences in the event of a serious accident in the transportation of such elements. Initially, it was decided to focus attention on the possibilities of gamma exposure from an unshielded but integral fuel element, since the possibility of a vapor release of the container fission products appears to be rather remote.

As an example of the type of analysis that is possible, and is currently applied to other types of nuclear hazards, the following evaluation was made. The results are summarized below.

1. Gamma Exposure from a Radioactive Source

An approximate treatment of gamma exposure from radioactive sources can be based on the inverse square law of radiation attenuation for point sources, i.e. the size of the source is assumed to be small in comparison with the distance separating it from the point of observation. If the radiation from a point of strength Q mev/sec is emitted uniformly in all directions, than at a distance d cm. from

the source, the energy flux will be distributed uniformly over the surface of a sphere of area $4\pi d^2 cm^2$. Neglecting the absorption of energy in air, the energy flux at a distance d cm from the unshielded source is approximately $Q/(4\pi d^2)$ mev/cm^2-sec. Introducing a factor K which includes the energy flux to dose rate conversion factors as well as attenuation parameters, the dose rate I r/hr at distance d cm from the source is given generally by the equation:

$$\text{Gamma Dose Rate} = I = KQ/d^2 \text{ roentgens per hour}$$

and the integrated dose D(t) received during the time interval from t_1 to t_2 is given generally by the equation:

$$\text{Gamma Dose} = D(t_1 t_2) = \int_{t_1}^{t_2} I\,dt = \int_{t_1}^{t_2} \frac{KQ}{d^2}\,dt \text{ roentgens}$$

It will be observed that according to these equations the dose rate and dose are inversely proportional to the square of the distance from the source. It is this relationship which makes appreciable separation from a radioactive source an important factor in radiation protection. It should be pointed out that these equations are by no means exact, since several approximations have been introduced, such as considering the energy absorption in air independent of the various photon energies of the source and the distance from the source as well as the assumption of a point source. More exact treatments are possible, but such considerations are omitted at the present time in order to simplify the estimation of order of magnitude values.

Extending the inverse-square relationship, it is possible to determine dose rates and doses at different distances, when the exact source strength is unknown but rather the dose rate at a given

distance is known. This follows from the fact that: $KQ = I_o d_o^2 = I_1 d_1^2$, from which can be derived the following equations:

$$I_1 = I_o d_o^2 / d_1^2 \text{ r/hr}, \text{ and } D_1(t_1 t_2) = D_o(t_1 t_2) d_o^2 / d_1^2 \text{ r}$$

2. Critical Values for Gamma Exposure

In an AEC report, WASH-740, prepared by staff members of the Brookhaven National Laboratory, an attempt was made to estimate the consequences of major accidents in nuclear power plants. For the purposes of that study, critical values for gamma exposure were developed and used in the subsequent analysis. The following table of critical values are based on the Brookhaven report.

Critical Values for Gamma Exposure

Lethal Exposure	over 450 r
Injury likely	100 to 450 r
Observation likely .	25 to 100 r
Evacuation likely . .	over 0.002 r/hr

By combining these values with the inverse-square relationships developed above, it is possible to calculate the critical exposure distances and areas around the radioactive source. The general equations are:

$$\text{Critical Distance} = f_c = f_o(I_o/I_c \text{ or } D_o/D_c)^{-1/2} \text{ ft.}$$

$$\text{Critical Area} = \pi f_c^2 = \pi f_o^2 (I_o/I_c \text{ or } D_o/D_c) \text{ ft.}^2$$

3. Gamma Exposure from MTR Fuel Elements

In an AEC report, IDO-16247, by W. C. Francis and L. L. Marsden, the gamma decay dose rates from spent MTR fuel elements were determined experimentally for various reactor irradiation cycles and various cooling times. The dose rates for a one cycle fuel element, taken

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through 3" of water, from the centerline at different times after reactor shutdown, t = 20 to 200 days, were fitted to the following equation:

$$\text{Dose Rate @ 3"} = I_o(t) = 2.7 \times 10^7 t^{-1.21} \text{ r/hr}$$

The dose rate for a two cycle element was approximately double that of the one cycle element, and the three cycle element dose rate was approximately that of the two cycle element, indicating that an equilibrium existed.

The integrated dose at 3" for different exposure intervals, $t_2 - t_1$, where time is now given in hours, can be calculated by the following equation:

$$\text{Dose at 3"} = D_o(t_1,t_2) = 2.7 \times 10^7 \int_{t_1}^{t_2} (t/24)^{-1.21} dt \text{ roentgens}$$

$$= 6 \times 10^9 (t_1^{-0.21} t_2^{-0.21}) \text{ r}$$

The integrated dose at 3" for three different cooling times and three different exposure times were calculated using the above equation. The results are given in the following table.

Integrated Doses/(r) from a 1-Cycle MTR Element @ 3"

Cooling Time	Exposure Times		
	2 hours	24 hours	1 week
20 days	0.3×10^7	2×10^7	12×10^7
50 days	0.06×10^7	0.6×10^7	4.2×10^7
100 days	0.02×10^7	0.2×10^7	2×10^7

These results can be combined with inverse-square distance relationships, developed above, to give approximate estimates of the critical distances and areas according to the critical values developed previously.

The results of these calculations are given in the following table.

Critical Distances and Areas for Gamma Exposure from a 1-Cycle MTR Element

Approximate Distances and Areas per Exposure	Element Cooling Time in Days					
	20 Days		50 Days		100 Days	
	feet	acres	feet	acres	feet	acres
Two Hour Exposure:						
Fatality likely	20	--	10	--	5	--
Injury likely	45	0.2	20	--	10	--
Observation likely	85	0.6	40	0.2	25	--
24 Hour Exposure:						
Fatality likely	55	0.2	30	0.1	20	--
Injury likely	115	1.0	65	0.3	35	0.1
Observation likely	225	3.7	125	1.1	70	0.4
Evacuation likely	1.0 miles 1800 acres		0.6 miles 1150 acres		0.4 miles 300 acres	

As many as four MTR elements have been shipped in a single container, and if the unshielded source consists of four elements, the critical areas are increased by a factor of four and the distances by a factor of two, according to the approximate relationships used. Furthermore, if the element(s) have been irradiated in the reactor for two or more cycles, the areas would be approximately doubled and the distances increased by a factor of $2^{1/2}$.

4. Valuation of Gamma Exposures

In the Brookhaven report mentioned above, the potential losses resulting from reactor accidents were reported in terms of: the number of persons probably killed, injured, observed, and evacuated, and the dollar cost for evacuation. The method of estimating costs for the latter value involved the calculation of an average dollar cost per person for long-term evacuation, and temporary evacuation or severe restriction on mode of living. In addition a cost per square mile

was developed for destruction of standing crops with restrictions on farming for one year as a result of radioactive fallout. The cost for temporary evacuation was estimated at $750 per person. This figure was based on an evacuation period of as long as six months. Since the evacuation period considered here is probably much shorter, an estimate of $100 per person seems more appropriate. No attempt was made to estimate the cost of death, injury, and observation in the Brookhaven report.

Available population statistics for the United States indicate the wide variability in densities for different parts of the country. Population densities for Baltimore City (1948) range from approximately 150 persons/acre in the center of the city to 2-5 persons per acre nearer the city limits. The average density for the City was 20 persons per acre. The average density for the Baltimore Metropolitan Area was approximately 2.24 persons per acre, and 0.5 for surrounding suburban areas. The Brookhaven report indicates the average density for the industrial northeastern States is approximately 1.0 persons per acre, and for the entire nation the average is about 0.1 persons per acre. In order to obtain an estimate of the number of persons affected by the gamma exposures developed above, the following estimates are used, and the corresponding evacuation costs based on $100 per person are shown.

Population Densities and Evacuation Costs

Area	Pop. Density	Evacuation Cost
Large City	20 persons/acre	$2,000/acre
Suburban	2 persons/acre	200/acre
Rural (highway)	0.5 persons/acre	50/acre

In order to determine the number of persons exposed to significant gamma dosages, it is necessary to know the exposure time as well as their proximity to the source. The gamma exposures calculated previously were based on two exposure periods, two hours and 24 hours, which represent the time required to effect evacuation of bystanders and occupants from the area surrounding the source. It is readily apparent that with the arbitrarily limited possible combinations of such factors as: number of elements (1 to 4), cycle times (1,2), cooling times (20, 50, 100 days), population densities (1, 2, 20 persons per acre), and evacuation times (2, 24 hours), that have been cited, a very large number of different results are possible, i.e. 4 x 2 x 3 x 3 x 2 = 144 possibilities.

An estimate of the evacuation costs associated with exposure to a single unshielded 1-cycle MTR fuel element are given below. These values are independent of the evacuation period, but would be doubled for a 2-cycle element and also multiplied by the number of elements included in the source.

Evacuation Costs for a Single 1-Cycle MTR Element

Area of Exposure	Element Cooling Time		
	20 Days	50 Days	100 Days
Rural	$ 90,000	$ 57,500	$ 15,000
Suburban	360,000	230,000	60,000
Urban	3,600,000	2,300,000	600,000

An estimate of the number of persons affected by exposure to a single, unshielded, 1-cycle, 20 day, MTR element, if evacuation is delayed one day, has been calculated as one of the more extreme situations. The results are given on next page.

Persons Affected by Exposure to a Single, 1-Cycle, 20 Day Old, Unshielded MTR Element in 24 hours

Area of Exposure	Type of Exposure			
	Fatal Dose	Injury	Observation	Evacuation
Rural	none	none	2	900
Suburban	none	2	7	3,600
Urban	4	20	70	36,000

These results are presented only as an example. It is planned to continue research on this problem, in an attempt to devise a more realistic method of evaluating such hazards.

5. Expected Hazard Costs

The evaluation of the possible consequences of exposure to a radioactive source, such as an MTR fuel element, indicates the wide variability of the "consequences" due to such factors as the strength of the source, population density, and evacuation time. As an alternative procedure to evaluating each discrete possibility, it is possible to treat the consequences as a continuous variable with a probability density over an entire range of values, measured in terms of total dollar cost for example. It would then be possible to utilize "typical" values to represent the distribution of costs, i.e. the average, mean, or expected value and, possibly, certain confidence limits. It may also be possible to simplify such an analysis by identifying the cost distribution with known distributions which can be fully described by a few parameters. This same approach may be employed in the evaluation of the "frequency" of nuclear hazards.

For example, the underlying statistical theory for traffic accident frequency studies is based on the poisson distribution,

which is particularly suited to the observation of discrete random events over time or distance, and can be used to determine the expected accident rate within given confidence limits. This distribution can be applied to the occurrence of industrial accidents, and in particular to atomic accidents. Comparable statistical theory for the distribution of accident costs has not been found in the available literature; however, a preliminary analysis of motor vehicle accident data made available to the project indicates that the accident cost data may be characterized by a lognormal distribution. This distribution has been used extensively to describe the distribution of income and other economic data. It is also used to describe such varied data as equipment failures, toxicity of poisons, and rock breakage in geological formations. There appears to be a good possibility that it may be used to approximate the hazard distribution with a poisson hazard frequency and lognormal cost severity.

It has been shown that when events occur with a poisson frequency in a given sample space or period of time, and the value of such events is distributed lognormal, then the total worth of the sample space is also distributed lognormal. If it is possible to develop analogous measures for the frequency and cost of nuclear hazards, the end result is a loss function for a given nuclear exposure; for example, it would be possible to fully determine the distribution of losses for a particular shipment of radioactive materials. If we represent the loss function (or density) of the shipment by the expression f(x) where the cost x ranges from zero

to infinity, then the expected loss for the shipment can be expressed as:

$$\text{Expected Loss} = E(x) = \int_0^{\infty} x \cdot f(x)\,dx$$

If for some reason, the actual paid losses are limited to a maximum amount for any given event, the above expression can be modified to give the expected paid losses for the shipment, by denoting m = maximum paid loss for any one event; then:

$$\text{Expected paid losses} = E(x,m) = \int_0^{m} x \cdot f(x)\,dx + \int_m^{\infty} m \cdot f(x)\,dx$$

It is planned to continue research along these lines in an attempt to measure the hazards associated with shipments of radioactive materials.

V. EXAMPLES AND APPLICATIONS

A. Shipment of Liquid Wastes over Long Routes

Early in the project it was decided to develop an elementary model for the total transportation cost of a shipment, including hazard cost, and apply the model to long haul shipments between two facilities in order to demonstrate its applicability to the problem. This work was reported in a paper entitled, "An Operations Research Study of the Transportation of Highly Radioactive Materials," and presented at the Fourth Joint Military-Industry Packaging and Materials Handling Symposium, sponsored by the Office of Naval Materials, Department of Navy, October 1, 1958, in Washington, D. C. Approximately one hundred and fifty copies of this paper were distributed within the A.E.C. and to a number of other interested parties. The original model and application is presented below in a more abbreviated form.

The material shipped, its origin and destination, and the transportation mode and vehicle are specified and held fixed. Variations are made in the route, escort, and container. The original model expresses the total transportation cost (T) as the sum of the package cost (P), the shipping cost (S), and the expected hazard cost (H), which are functions of three variable factors: the container (C), the escort (E), and the route (R). The model is written as follows:

$$T(C,E,R) = P(C,R) + S(E,R) + H(C,E,R)$$

where: $P(C,R)$ = package cost as a function of container and route;

$S(E,R)$ = shipping cost.

$H(C,E_1R)$ = expected hazard cost

This equation was evaluated for shipments of an arbitrarily specified liquid material between Idaho Falls, Idaho, and Oak Ridge, Tennessee, by tractor-trailer truck combination. Three different routes were selected, three different containers were specified, and shipments could be made with or without escort. Because of the unavailability of actual data, hypothetical data is used throughout using values that appeared to be reasonable.

1. Routes and Mileage Classifications

Three truck routes were chosen from Idaho Falls to Oak Ridge using major transcontinental highways. The central route (R_1) is the shortest route, 1,974 miles, via Kansas City, St. Louis, and Nashville. The northern route (R_2) is the next shortest, 2,038 mi., via Sioux City, St. Louis, and Louisville; and the southern route is the longest, (R_3), 2,136 mi., via Salt Lake City, Wichita, and Nashville. It was determined that in addition to total mileage, the cost of a shipment would be affected by such factors as rise and fall, urban development, and the proximity to critical environmental features such as watersheds and dense populations. Therefore, the total mileage for each route was sub-divided into six mileage classifications using topographical maps and arbitrary judgment. The six mileage classifications used were:

Mileage Classifications (j)

j = 1. Rural, level, non-critical
2. Rural, level, critical
3. Mountain, non-critical
4. Mountain, critical
5. Urban, non-critical
6. Urban, critical

The determination of critical rural and mountain miles was made on a basis of the proximity of the road to water-sheds; and approximately 1/2 of the urban miles were classified as critical with respect to population and water and sewage systems. The total mileage for the three routes was classified as follows:

Mileage Classification for Three Routes, $m_j(R)$

Class	Central (R_1)	Northern (R_2)	Southern (R_3)
j - 1	711 mi.	804 mi.	753 mi.
2	454	387	317
3	635	680	964
4	25	34	13
5	96	87	57
6	53	46	32
Total	1,974 mi.	2,038 mi.	2,136 mi.

2. Containers and Hazard Frequencies

Three containers were specified arbitrarily as: (C_1) a minimum strength container, (C_2) a medium strength container, and (C_3) a maximum strength container. The strength of a container was measured by its ability to prevent any major spillage or release of material in the event of an accident, i.e. material is not released to the environment but confined to the vehicle or container. It was decided, further, that the cost of containers would vary with the strength, and the following values were specified as the depreciation cost per mile for the three containers:

Container Depreciation Cost per Mile

Container Design (C)	Cost per mile P(C)
C_1 Minimum Strength	$ 0.25 per mile
C_2 Medium Strength	0.50 per mile
C_3 Maximum Strength	1.00 per mile

The expected hazard frequency was developed from truck accident statistics, showing the frequencies of accidents by type, i.e. head-on, rear-end, overturn, etc. Each of these accident frequencies was multiplied by the probability that such an accident would result in four different kinds of atomic hazards, i.e. minimum damage, shield damage, minimum spill, and maximum spill. These probabilities were necessarily arbitrary, since such information is not available. The combined probabilities for each of the four hazards were then summed over all accidents, giving an expected hazard frequency per 100,000 miles by type and mileage classification. The results of these calculations are shown below for the three containers by rural (including mountain) and urban miles. This frequency is denoted by (ajk).

Expected Hazard Frequency per 100,000 (ajk)
by Container and Route Classification

Container Design and Route Classification			Minimum Damage k = 1	Shield Damage k = 2	Minimum Spill k = 3	Maximum Spill k = 4	Total All Accidents
C_1	Rural	j = 1-4	0.7215	0.1810	0.0810	0.0165	1.0000
	Urban	j = 5,6	1.7300	0.2056	0.0520	0.0124	2.0000
C_2	Rural	j = 1-4	Same as above -		0.0892	0.0083	1.0000
	Urban	j = 5,6			0.0582	0.0062	2.0000
C_3	Rural	j = 1-4	Same as above -		0.0975	0.0000	1.0000
	Urban	j = 5,6			0.0644	0.0000	2.0000

3. Escort and Hazard Costs

Shipments were permitted with and without escort by a separate patrol vehicle and driver. The two choices are designated (E_1) with escort, and (E_2) without escort. The cost for providing escort was determined in the same manner as for determining the truck freight

cost for the shipment. A basic cost per level, rural mile was determined; and this was increased by a factor of 1.5 for mountain miles and a factor of 1.25 for urban miles, as a simple expedient for indicating the increased vehicle and time cost for different route classifications. These costs are presented below.

Escort and Freight Costs by Mileage Classification

Mileage Classification	Escort Cost $C_j(E_1)$	Freight Cost f_j
Rural j = 1,2	$0.28 per mi.	$0.42 per mi.
Mountain j=3,4	0.42 " "	0.63 " "
Urban j = 5,6	0.35 " "	0.53 " "

A hypothetical hazard cost table was constructed to correspond to the different hazard frequency categories developed above. It was decided to distribute the costs in an arbitrary but reasonable fashion between two extreme values, allowing for a reduction in costs due to the presence of escorts, which would probably effect a considerable reduction in the time necessary to control the accident consequences. The extreme values chosen were $2,000 for a minor damage accident with escort to cover the cost of inspection and verification that no major damages occurred, and $100,000,000 for a major release of highly radioactive liquids in a critical urban environment without escorts. The cost per hazard accident by mileage classification is denoted by (b_{jk}) and are given on next page.

Hypothetical Hazard Costs by Location and Escort (b_{jk})

Escort System and Mileage Classification (j)			Minimum Damage k = 1	Shield Damage k = 2	Minimum Spill k = 3	Maximum Spill k = 4
E_1 Rural,	Mtn.	j = 1,3	$ 2,000	$ 10,000	$ 50,000	$ 1,000,000
"	Crit.	j = 2,4	"	"	"	10,000,000
Urban		j = 5	"	20,000	100,000	7,500,000
"	Crit.	j = 6	"	"	"	75,000,000
E_2 Rural,	Mtn.	j = 1,3	5,000	25,000	200,000	2,500,000
"	Crit.	j = 2,4	"	"	"	25,000,000
Urban		j = 5	"	50,000	500,000	10,000,000
"	Crit.	j = 6	"	"	"	100,000,000

4. Expected Hazard Costs

In the analysis above, the two hazard parameters developed are the frequency (a_{jk}) of type "k" hazardous accidents per class "j" mile, and the cost (b_{jk}) for a type "k" accident in a type "j" location. Assuming these parameters fully describe the possibilities for a hazardous accident to occur, it is possible to derive the "expected hazard cost per mile" for each class of mile, denoted by (h_j), where:

Expected Hazard Cost per Mile = $h_j = \sum_k a_{jk} b_{jk}$ (j = 1-6, k = 1-4)

The four cost possibilities, multiplied by their respective frequencies, are summed for each mileage class. Since the frequency is a function of the containers ($C_1C_2C_3$), and the cost is a function of the escort system (E_1E_2), there are six different h_j for each of the six different mileage classes. The 36 possible values for h_j were calculated using the above data. The results are shown in the following table.

Expected Hazard Cost (h_j) per Mile

Mileage Classification		Container and Escort Combinations					
		C_1,E_1	C_2,E_1	C_3,E_1	C_1,E_2	C_2,E_2	C_3,E_2
Rural, Mtn., non-crit.	j = 1,3	$ .24	0.16	0.08	0.66	0.47	0.28
Rural, critical	j = 2,4	1.72	0.91	0.08	4.37	2.33	0.28
Urban, non-critical	j = 5	1.06	0.60	0.14	1.65	1.10	0.51
Urban, critical	j = 6	9.43	4.78	0.14	12.65	6.68	0.51

The expected hazard costs vary from a low of $ .08 per mile for shipments in a maximum strength container (C_3) with escort (E_1) for non-urban, non-critical mileages (j = 1,3), to a high of $12.65 per mile for shipments in a minimum strength container (C_1) without escort (E_2) for urban, critical mileages (j = 6).

5. Total Costs per Mile

The total cost equation can now be expanded to include the various parameters developed above. The original model was:

$$T(C,E,R) = P(C,R) + S(E,R) + H(C,E,R)$$

where: Container C = C_1,C_2,C_3; Escort E = E_1,E_2; and Route R = R_1,R_2,R_3

Package Cost $P(C,R) = p(C) \sum_j m_j(R)$ j = 1-6

Shipping Cost $S(E,R,) = \sum_j [f_j + e_j(E)] m_j(R)$

Hazard Cost $H(C,E,R) = \sum_j \sum_k a_{jk}(C) b_{jk}(E) m_j(R) = \sum_j h_j(C,E) m_j(R)$

The expanded total cost equation is:

$$T(C,E,R) \quad \sum_j [p(C) + f_j + e_j(E) + h_j(C,E)] m_j(R) \quad j = 1-6$$

By setting: $c_j(C,E) = p(C) + f_j + e_j(E) + h_j(C,E)$, the total cost equation is greatly simplified to:

$$T(C,E,R) = \sum_j c_j(C,E) m_j(R) \qquad j = 1-6$$

Values for the combined cost parameter c_j, which is the total transportation cost per mile for each of the six mileage classifications (j), are given on next page.

Total Cost per Mile (c_j)

Mileage Classification		Container and Escort Combinations					
		C_1,E_1	C_2,E_2	C_3,E_1	C_1,E_2	C_2,E_2	C_3,E_2
Rural, non-critical	j 1	$1.19	$1.36	$1.78	$1.33	$1.39	$1.70
Rural, critical	2	2.67	2.11	1.78	3.04	3.25	1.70
Mountain, non-crit.	3	1.54	1.71	2.13	1.54	1.60	1.91
Mountain, critical	4	3.02	2.46	2.13	5.25	3.46	1.91
Urban, non-critical	5	2.19	1.98	2.02	2.43	2.13	1.54
Urban, critical	6	10.56	6.16	2.02	13.43	7.71	1.54

6. Solution and Results

Using the mileage classifications for the three routes, which were developed in Section 1 above, it is now possible to determine the total cost for the three routes. The results of these calculations are given below.

Total Costs for Three Routes

Route	Container and Escort Combination					
	C_1,E_1	C_2,E_1	C_3,E_1	C_1,E_2	C_2,E_2	C_3,E_2
Central R_1	$3882	$3589	$3781	$5288	$4179	$3471
Northern R_2	3816	3612	3910	5075	4121	3593
Southern R_3	3729	3539	4165	4720	4015	3822

The minimum cost combination is $T(C_3,E_2,R_1) = \$3471$, i.e. shipment in the maximum strength container, without escort, via the shortest route. It is interesting to note that the minimum cost solution corresponds to the thinking of many of the people concerned with the problem; and the hypothetical result might appear to justify a policy of building strong containers at premium prices. However, a comparison of the various costs indicates that the minimum cost is sensitive to variations in the route. For example, the minimum

cost combination for the Southern route, because of its particular mileage composition, calls for shipments using a medium strength container without escort, rather than using a maximum strength container without escort, which is the best combination for the Central and Northern routes. Thus, it is not generally true, on the basis of the hypothetical results, that there is one best combination for all routes, but rather that different routes may call for different container designs and escort provisions.

On the other hand, different containers may call for different route selections and escort provisions. Referring again to the above table, the minimum strength container C_1 and the medium strength container C_2 are best shipped by the Southern route with escort, while the maximum strength container C_3 is best shipped by the Central route without escort. This would indicate that for shipments in less than maximum strength containers, the reduction in hazard by providing escort and avoiding large cities more than offsets the increased costs of such precautions.

B. Shipment of Fuel Elements through Metropolitan Areas

During the past summer, as recorded in "An Operation Research Study of the Transportation of Highly Radioactive Materials," (Leimkuhler and Thompson) an exploration was made of a first model which considered as primary variables of total transportation cost, the costs of packaging, freight, safety, and hazard or, put another way, the costs of containers, operation of vehicles, escort, and expected hazard. This total cost was to be minimized. As was pointed out in that paper, these variables are influenced by the nature of the material in transport, the route, and several other factors.

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In this first model we chose as the material one in which some shipping experience was available. This was 500 gallons of Redox, a liquid waste. This choice dictated a fifteen ton cylindrical container whose characteristics were known and this, in turn, fixed the selection of the vehicle, a heavy 5-axle tractor-semitrailer, the mode, by highway, having been previously been decided on.

The three highway routes selected lay between Oak Ridge, Tennessee, and Idaho Falls, Idaho; they were widely separated and involved differing characteristics as to topography, population distribution, length, and environment generally.

Working with the first model and example, as influenced by the choices and determinations mentioned above, we discovered that it was too big and too complex for the present status of our knowledge. The material, a liquid, had a high dispersability which complicated hazard cost and the routes were too long and so far removed from our headquarters that they became abstract and difficult to obtain information about.

Moreover, we learned that the big problem lay in what to do about population centers -- whether to go through them, or if the alternative exists, to go around them. We also observed, working with maps, that route details, in between population centers tended to be very repetitious, and that one could learn as much from a much shorter set of routes.

Accordingly, late in the fall of 1958, we decided to work with a different set of choices, designed to correct these faults. A solid rather than a liquid was selected. This consisted of four MTR fuel elements with the concomitant 26,000 pound shipping vessel

described in AECU-3254, "Transportation Costs for Irradiated MTR Fuel Elements," June 1956.

As before, three routes were selected, this time in the immediate vicinity of a large metropolitan city. Connecting two points, one to the northeast of the city and one to the west, we chose one route directly through the city following the official truck route. Another follows the county (circumferential) beltway which circumstribes the northern part of the city with a radius of about ten miles -- sufficient to carry it beyond the suburbs. It is a multiple lane, divided highway with full access control. The third route similarly circumscribes the southern half of the city and is made up of a harbor tunnel, and its approaches, a toll facility, and the southwestern sections of the beltway described above.

Contacts with state, city and county officials have provided all the information that may be desired -- items such as plans and profiles, design details, right-of-way widths, traffic volumes, speed limits, population distribution by census tracts, etc.

Bibliography

1. Aitchison, J. and Brown, J.A.C., The Lognormal Distribution, Cambridge 1957.

2. Arnold, E.D., at al., Compilation and Analysis of Waste Disposal Information, CF-57-2-20, Oak Ridge, March 1957.

3. Atomic Energy Facts, U.S. AEC, Washington, 1957

4. Butler, R., Liability Insurance in the United States, No. 57AIF80, Atomic Ind. Forum, New York, October 1957.

5. Brookhaven Staff et al., Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants, WASH-740, 1957.

6. Bureau of Explosives, AAR, Handling Radioactive Materials when Involved in Leakage Fires, New York, June 1958.

7. Callahan, A.D., et al., Nuclear Safety Guide, TID-7016, Oak Ridge, 1957.

8. Campbell, H.A., ICC Regulations for Transportation of Explosives and other Dangerous Articles, Tariff No. 10, New York, May 1957.

9. Churchman, Ackoff, and Arnoff, Introduction to Operations Research, Wiley, New York 1957.

10. Crosby, J. R., Accident Experience on the New Jersey Turnpike, N. J. Turnpike Authority, September 1958.

11. Culler, F. L., Comments on the Transportation of Irradiated Fuel and Radioactive Wastes for M. Louis Armand, Euratom Group, CF-57-5-24, Oak Ridge, May 1957.

12. Culler, F. L., Notes on Fission Product Wastes from Proposed Power Reactors, CF-55-4-25, Oak Ridge, March 1955.

13. Day, B. B., Application of Statistical Methods to Engineering, Rev. Inst. Int. Stat., Vol. 17, p. 129.

14. Duncan, A. J., A Statistical Guide for Accident Research, Op. Res., Vol. 3, No. 1, Feb. 1955.

15. Dunman, R., The Economic Costs of Motor Vehicle Accidents, HRB, Wash., January 1958.

16. Evans, R.D., Problems Associated with the Transportation of Radioactive Substances, National Academy of Sciences, Wash., 1951.

17. Feller, W., An Introduction to Probability Theory and its Applications, Wiley, New York 1950.

18. Fitzgerald, J.J., Hurwitz, H., and Tonks, L., Method for Evaluating Radiation Hazards from a Nuclear Incident, KAPL-1045, 1954.

19. Francis, W. C., and Marsden, L. L., Experimental and Theoretical Values of the Gamma Decay Dose Rate and Heating from Spent MTR Fuel Elements, IDO-16247, Idaho Falls, January 1956.

20. Glasstone, S., Principles of Nuclear Reactor Engineering, Van Nostrand, 1957.

21. Glaze, C.K., et al., Washington Motor Vehicle Operating Cost Survey, 1952-53, Washington State Highway Commission, Olympia.

22. Hayes, D. F., A Summary of Accidents and Incidents Involving Radiation in Atomic Energy Activities: June 1945 to Dec. 1956, TID-5360, 1956,(suppl.) 1957.

23. Handling, Shipping, and Storage of Solid and Liquid Fueled Missles and their Components, Redstone Arsenal, October 1958.

24. Highway Research Board, Accident Analysis and Impact Studies, No. 142, Washington 1956.

25. Hurst, L. K., Some Problems Associated with the Transportation of Spent Fuel Elements, Argonne National Laboratory.

26. Interstate Commerce Commission, Accident Data - Motor Carriers of Property, Washington, quarterly.

27. Inst. of Makers of Explosives, Safety in the Handling and Use of Explosives, New York, August 1951; Suggested State Law on Explosives, No. 3, 1956; Suggested City Ordinance on Explosives, No. 4, 1956; Rules for Storing, Transporting, and Shipping Explosives No. 5, 1956.

28. Joseph, A. B., Transportation of Radioactive Materials in the Atomic Energy Industry - A Study of Technical and Administrative Aspects (Draft), AEC, Washington 1958.

29. Joseph, A. B., Radioactive Waste Disposal Practices in the Atomic Energy Industry, The Johns Hopkins University, Baltimore, December 1955.

30. Kiewit, F., Geiger Counter as Vital as Gasoline, Kansas City Star, March 16, 1958.

31. Leimkuhler, F. F., and Thompson, J. T., An Operations Research Study of the Transportation of Highly Radioactive Materials, The Johns Hopkins University, Baltimore, October 1958.

32. Malquist, G.L., et al., Cost of Transporting General Freight by Motor Vehicle Equipment in the State of California, Case No. 5432, California Public Utilities Commission, January 1957.

33. Matlock, H., et al., High Velocity Impact Cushioning, University of Texas, Austin, Texas, August 1957.

34. McCullough, C.R., Interpretation of the Purpose, Scope, and Operation of the Reactor Safeguards Committee, AIChE Preprint No. 1, New York, Dec. 1955.

35. McCullough, C. R., The Experience in the United States with reactor Operation and Reactor Safeguards, AEC Reactor Safeguards Committee, Washington 1958.

36. Menegus, R.L., and King, H.F., Accidental Dispersion of Reactor Poisons and the Controlled Distance Required, DP-105(Rev.2), 1958.

37. Murphy, A.W., et al., Financial Protection against Atomic Hazards, Atomic Ind. Forum, New York, January 1957.

38. Naddor, E., Simplified Models in Operations Research, from Flagle, C.D., Huggins, W.H., and Roy, R.H., O.R. and Systems Eng'g, Johns Hopkins Press, 1959.

39. Norden, M., Orlansky, J., and Jacobs, H., Statistical Analysis of Highway Accidents, HRB No. 117, Washington 1956.

40. Nuclear Energy Liability Policy (Suppliers' and Transporters' Form) Nuclear Energy Liability Insurance Assn., New York, May 1957.

41. Pasarew, I.A., a Functional Plan for the Baltimore Metropolitan District, Maryland State Planning Commission, April 1948.

42. Pittman, F.K., AEC Licensing Policies and Precedures, Atomic Ind. Forum No. 207, Dec. 1955.

43. Piper, W.H., and Langhaar, J. W., 70-Ton Shipping Cask for the Savannah River Plant - Design and Fabrication, DP-357, Wilmington, Del., January 1959.

44. Port of New York Authority, Rules and Regulations Governing the Transportation of Explosives and Other Dangerous Articles, July 1958.

45. Price, H., Problems of Government Indemnification, Atomic Ind. Forum, October 1957.

46. Radiation Hazards of Radioactive Isotopes in Fire Emergencies, and Radiation Hazards in Firefighting, Int. Assn. of Fire Chiefs, New York 1955.

47. Radiation Hazards in Firefighting, Safety and Fire Prot. Tech. Bul. No. 4, AEC Wash.

48. Rockwell, T., et al., Reactor Shielding Design Manual, TID-700, March 1956.

49. Rogers, C.F., et al., Time and Gasoline Consumption in Motor Truck Operation, HRB No. 9-A, Washington 1950.

50. Rupp, A.F., Shipping Container Design, Memo to AEC ad hoc Committee on Transportation, Washington, July 1956.

51. Security Shipment Emergencies, (Rev.), Oak Ridge, July 1955.

52. Siddall, E., Statistical Analysis of Reactor Safety Standards, Nucleonics, V. 17, No. 2, pp. 64-69, February 1959.

53. Spencer, E.M., The Insurance Problem, AIChE, No. 208, New York, December 1955.

54. Transportation Costs for Irradiated MTR Fuel Elements, AECU-3254, Washington 1956.

55. Wendt, G., The Prospects of Nuclear Power and Technology, Van Nostrand, New York, 1957.

56. Wise, W.R., Investigation of Strain-Energy Absorption Potential as the Criterion for Determining Optimum Reactor Vessel Containment Design, NAVORD 5748, June 1958.

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Studies were made on the treatment of wastes from the laundry for contaminated clothing at Los Alamos. The wastes contained soap, synthetic detergents, citric acid, and lint. The 5-day B.O.D.'s of the wastes varied from about 200 to 600 p.p.m. The alpha activity from plutonium was relatively low, averaging about 1500 counts per minute per liter, but maxima of 20,000 counts per minute per liter were observed. The objective in treatment was to reduce the plutonium activity in the discharged effluent to 70 counts per minute per liter or less. A reduction in the B.O.D. was desirable but of secondary importance.

Experiments indicated that biological treatment was superior to chemical treatment. Chemical treatment (carrier precipitation) might not be entirely successful because of coagulation difficulties caused by complexing agents. Activated sludge treatment was not feasible on detergent wastes because of excessive foaming. When the waste was deficient in biological nutrients, ammonia and phosphate were added to the laundry waste prior to biological treatment. The single-stage pilot trickling filter was ineffective in B.O.D. or plutonium removal with recirculation ratios of 8 to 1 or less. With recirculation ratios of 15 to 1 and higher, analytical results indicated nitrification, 90 percent or more B.O.D. removal, and satisfactory plutonium removal.

The work indicates that the plutonium removal objective can be attained either chemically or biologically. Simplicity of operation and volume of sludge to be disposed of seem to favor biological treatment.

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Laboratory Studies on Removal of Plutonium from Laundry Wastes

The primary function of a laundry at any atomic energy installation is the removal of radioactive material from garments and equipment. A secondary and almost equally important function is the actual removal of ordinary types of soil. At Los Alamos the laundry operation is very similar to that of the ordinary commercial laundry. However, because of the decontamination requirements, the washing operations require large quantities of synthetic detergents, and more washing and rinsing per operation cycle. Starching, ironing, and finishing operations are absent.

Materials used in the laundering operations include soap and synthetic detergents, ammonium citrate, ammonium fluosilicate, and occasionally some phosphates. The resulting waste has a 5-day biochemical oxygen demand (B.O.D.) ranging from 100 to 600 p.p.m. and which will average about 350 p.p.m. The total solids average about 700 p.p.m. The suspended solids average about 100 p.p.m. of which about 60 p.p.m. are settleable. The B.O.D. is substantially lower than the oxygen consumed value run by the procedure described by Moore *et al.* (*3*). The reason for this is that the wastes contain a synthetic detergent resistant to biochemical oxidation but readily oxidized chemically. The detergent in question is Igepal CA Extra which is a polymerized ethylene oxide.

Plutonium 239, an alpha emitter with a half life of about 24,000 years, is the only consequential radioactive material in the waste. The plutonium content of the waste will average about 1000 counts per minute per liter with minimum to maximum variations from 100 to 20,000 counts per minute per liter. (One microgram of plutonium is equivalent to about 70,000 counts per minute). The higher concentrations which have been of infrequent occurrence, presumably resulted from the laundering of highly contaminated materials following extraordinary operations.

It is imperative that the hazardous and toxic materials be removed from the wastes before they are discharged. The primary objective for treatment of this or any other radioactive waste is the removal of the radioactive contaminants. For other obvious public health reasons an important secondary objective in treating the laundry wastes is the removal of the B.O.D. Over the past years the various public health agencies have established standards for permissible

B.O.D. levels that may be discharged into receiving streams; however, since the atomic energy industry is in its infancy, these agencies do not as yet have the necessary information for the establishment of permissible levels of radioactivity which may be discharged. The Atomic Energy Commission and its contractors have established tentative permissible discharge levels or tolerance values for various types of radiation. It is obviously desirable to develop an economical liquid waste treatment process which will more than comply with minimum tentative standards. On this basis the ultimate objective of one thousandth of a microgram per liter was tentatively selected as the maximum desirable concentration of plutonium in the treated waste.

At the time this goal was established this quantity was well below the tentative permissible plutonium concentration in drinking water. One thousandth of a microgram of plutonium is equivalent to about 140 disintegration per minute per liter. Since the counting equipment has a 50% geometry the 140 disintegrations are recorded as 70 counts. For conversion to curies it should be remembered that 1 curie is equivalent to 3.7×10^{10} disintegrations per second.

At present the laundry wastes are discharged into a series of two open gravel beds. The gravel beds were designed to function very much like a slow sand biological filter. In practice, however, these beds have become clogged with soap curds and lint resulting in very little percolation of the laundry effluent through the sand.

The laundering operation must be designed to have a maximum of success in dissolving or suspending and dispersing the plutonium content of the materials processed. This naturally results in a waste containing agents which are efficient in holding the plutonium content in solution or stable dispersion. Accordingly, it would be anticipated that the laundry wastes would be more difficult to treat than the laboratory wastes previously discussed by Christenson *et al.* (*1*).

CHEMICAL TREATMENT

The success of ordinary precipitation operations with lime and iron or alum in removing plutonium from distilled water or laboratory wastes naturally resulted in the investigation of similar processes for application to the laundry wastes. At this point, it may be noted before discussing the results obtained in these flocculation experiments that all the work included rapid mixing while the reagents were added, followed by a half hour of gentle agitation before further steps were undertaken.

The first attempts to use precipitation methods on samples of this waste resulted in dismal failure. Extensive experimentation failed to yield any method which gave a good coagulation using alum. Ordinary dosages of ferric chloride (up to 100 p.p.m.) also failed to give satisfactory results. It was possible to get a consistently satisfactory floc which would remove plutonium and settle and filter well only with a large dose of iron and lime followed by pH adjustment to 11.5 and higher with sodium hydroxide. Later, the addition of about 100 p.p.m. of calcium chloride assisted in tying up the complexing agents and resulted in some improvement in coagulation. As a further step, 20 p.p.m. of activated sodium silicate were added prior to the addition of the iron giving further improved flocculation. The effect of the order of addition of the chemicals was investigated and after some experimentation it was found that best results were produced without lime and by adding the other chemicals in solution or suspension as follows: 300 p.p.m. of calcium chloride, sodium hydroxide to pH 12.0, 20 p.p.m. of activated silica, and finally 60 p.p.m. of iron as ferric chloride. This is the procedure currently used, and with the samples encountered up to the present time it has effected satisfactory plutonium removal.

The initial plutonium values were run on straight wastes. The treated values were run on samples filtered through Whatman No. 2 fluted filter paper.

TABLE I.—*Removal of plutonium from laundry wastes by chemical treatment*

[Period of observation, March 9 to June 9]

	Suspended solids		Settleable solids, Ml./Liter	Plutonium concentration Counts/Min./Liter	
	P.p.m.	Percent ash		Initial	Treated
Max	966	83	120	3185	665
Min	150	29	20	176	4
Av	384	50	58.5	600	87

The results of plutonium removal by chemical treatment are listed in Table I. The suspended solids figures represent determinations performed on the mixed liquor after addition of the chemicals and flocculation. The settleable solids represent the amount of wet sludge to be expected from this treatment process. This figure indicates that the wet sludge volume will be about 5.85% of the total volume of wastes to be treated. During the period in which these observations were made the plutonium concentration in the waste was somewhat lower than the average previously reported. This fact is not too significant, however, because the original plutonium concentration in the wastes, within the limits observed, has not in itself influenced the success or failure of the treatment process. Unsatisfactorily plutonium removals resulted from poor coagulation caused by complexing agents and not because of plutonium concentration.

Since the treatment procedure described above has been adopted, no failures have occurred in the removal of plutonium to the desired goal. Therefore, it is reasonable to assume that the chemical precipitation method will provide an effective treatment process as far as plutonium removals go. It should be pointed out, however, that the settleable solids contain the radioactivity which has been removed from the waste. The problems involved in handling and disposing of radioactive sludge suggest that other processes should be considered for treatment of these wastes.

BIOLOGICAL PROCESSES

The study of biological processes was started at substantially the same time as the flocculation studies. Previous reports by Ruchhoft (*5*) and Newell (*4*) had indicated that plutonium in low concentrations could be removed from solution by the use of the activated sludge process. The presence of relatively large quantities of soaps and other surface active agents in laundry waste would cause foaming in any process employing bubble aeration. This difficulty ruled out the activated sludge process. Consequently, the biological trickling filter which contains biological active flocs similar to activated sludge and which requires no aeration was selected for study. In addition, it was anticipated that the operation of a trickling filter would produce lower volumes of waste radioactive sludge than a chemical precipitation process.

To inaugurate this phase of the investigation, a single stage trickling filter was constructed adjacent to the laundry waste discharge. The filter consisted of two 55-gallon drums, mounted in an upright position, one on the other, and filled with stones varying in diameter from 1 to 4 inches. A collection pan was attached beneath the lower drum to discharge into a cylindrical 5-gallon settling tank. A perforated metal plate was placed on the top surface of the rock. A tilting bucket of about 1-liter capacity was constructed and mounted on the top rim of the barrel. This tilting bucket provided intermittent dosing of the waste and discharged on the perforated plate which provided good distribution of the small flow over the entire surface of the filter.

Laundry waste containing about 10% by volume of secondary sludge from the Los Alamos municipal sewage treatment plant was applied to the filter starting on June 9. The rate of application was 200 ml. per minute, corresponding to about 1.25 million gallons per acre per day. Formation of the initial slime was slow; 3 weeks were required for the development of a sparse growth. Although microscopic examination of the slime indicated a normal biological flora, laboratory measurements of results of operation were unfavorable.

Recirculation of the filter effluent from the settling tank back through the filter at a ratio of 2 parts of effluent to 1 part of laundry waste was started on July 6. The application rate of the raw laundry waste was not changed. Operation results for this period were not favorable, analytical data showing less than 20% removal of the B.O.D. and no removal of plutonium.

On August 9 a stirring mechanism was installed in the settling tank to retain the sludge in suspension. The introduction of nitrogen and phosphorus into the laundry waste was started on August 19. The nitrogen and phosphorus additions were varied as follows:

Date	Nitrogen and Phosphorus Additions
8/19–8/31	7 p.p.m. ammonia nitrogen; 7 p.p.m. nitrate nitrogen; 14 p.p.m. phosphate
8/31–9/8	14 p.p.m. ammonia nitrogen; 14 p.p.m. nitrate nitrogen; 14 p.p.m. phosphate.
9/8–9/27	30 p.p.m. amomnia nitrogen as ammonium hydroxide, 15 p.p.m. phosphate

The dosage rate and recirculation ratio remained unchanged.

Operation results showed slight improvement as indicated by B.O.D. removals but the plutonium removal remained zero.

From August 29 to November 4 the recirculation ratio was increased to 4 to 1. The nitrogen feed was increased to 60 p.p.m. of amomnia nitrogen fed in the form of ammonium hydroxide. The phosphate feed was kept at 15 p.p.m. of phosphate which maintained phosphate in the effluent. On November 9 the recirculation ratio was increased to about 8 to 1. The increased recirculation was obtained by reducing the amount of raw waste applied, first to 0.6 million gallons per acre per day and then to 0.3 million gallons per acre per day. In spite of low temperatures (about 45° F.) the B.O.D. removals increased to the 60 to 70% range. At this time the soluble plutonium began to indicate response to treatment, showing about 20% removal.

Following a freeze of the filter on December 9 operation of the unit was suspended. Thereafter the filter unit was moved to a heated building and a second stage filter similar to the first was added. Biological growth was developed on both filters by feeding tap water containing 10% by volume of secondary sludge from the municipal sewage treatment plant, 150 p.p.m. of flour, 50 p.p.m. of dextrose, and 200 p.p.m. of soap. Supplementary nitrogen and phosphorus were added in slight excess of the following ratios:

1 part of nitrogen to 20 parts of B.O.D. in the waste.

1 part of phosphorus to 80 parts of B.O.D. in the waste.

These ratios have been previously reported by Huekelekian (*2*) as the minimum amounts of these elements which will provide a balanced food for the growth of microorganisms. The soap, flour, and sugar were gradually decreased and increasingly larger amount of laundry wastes were added.

Within 1 week, an active growth was evident in both filters. Beginning January 16, 1950 the filters were placed in operation as a series, two-stage unit with a 15 to 1 recirculation ratio. Ammonia and phosphates were added to the laundry waste to provide necessary nitrogen and phosphorus. For the first time analytical results showed nitrification of the waste, and at this time the B.O.D. removals increased to the 90 percent range and plutonium was also removed.

Over a period of 6 months the two filters were operated with various combinations of flow patterns and recirculation ratios. A flow diagram of one type of operation and recirculation arrangement investigated is presented in Figure 1. Throughout this 6-month period the raw feed was maintained constant at 50 ml. per minute corresponding to an application rate of 0.3 million gallons per acre per day on the primary filter. This amounts to about 150 pounds of B.O.D. per acre foot per day on the basis of the volume of the primary filter only.

Those observations made during a period of adjustment to a new operation pattern are less likely to reflect a true picture of performance. In preparing the data of Table II, the last six to fifteen observations corresponding to a fixed mode of operation have been used. It is felt that these observations, preceded by an adjustment period of at least 2 weeks in most cases, are more representative of what might be expected from a given mode of operation.

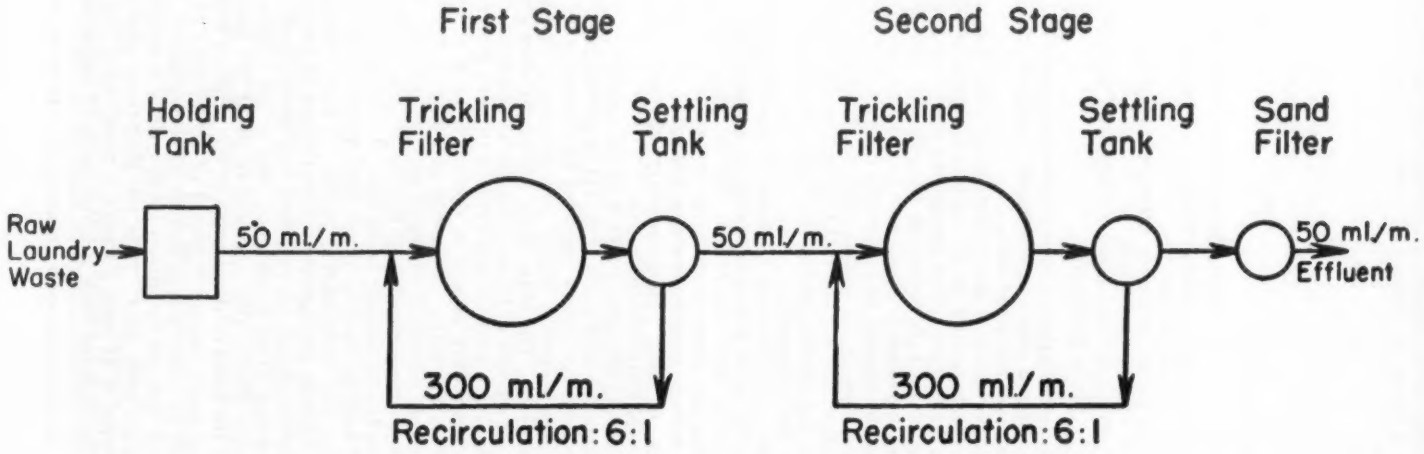

FIGURE 1.—Flow diagram of pilot plant for laundry waste disposal.

At certain periods in the early stages of the work it was noted that extraordinarily good plutonium removal coincided with the appearance of large quantities of nitrate in the effluent. In order to increase the nitrate in the effluent the amount of ammonia added with the raw feed was deliberately increased for several protracted periods of operation as is shown by the data of Table II. The two highest figures for nitrate content of the effluent are shown by the table to have occurred in the periods April 7 to April 24 and June 21 to July 10. The plutonium residue in the filtered effluent during the corresponding periods represents the lowest average values of plutonium residue attained.

Some of the variation in the results obtained may be due to factors other than those of application rate, ammonia feed, or recirculation ratios and arrangements. These uncontrolled factors include: 1, the variable nature of the waste in the matter of mineral and organic content; 2, variation in the amount and biological quality of the filter slime; 3, temperature variations.

It may be noted from Table II that in many cases the B.O.D. reduction produced by the second stage was exceedingly small. In any normal sewage plant trickling filter installation, it would be absurd to operate a second stage to reduce the B.O.D. of an effluent from 9 to 4 or from 26 to 3. However, these relatively inconsequential B.O.D. reductions are accompanied by very substantial reductions in the plutonium residue of the final effluent. Accordingly, a second stage is obviously desirable from the standpoint of the particular problem contemplated because it does show this plutonium removal. In terms of percentage removal of the original plutonium content of the waste, the removal in the second stage may be small. However, in terms of absolute plutonium content of the waste discharged, this removal is highly significant.

Throughout this work the phosphate feed was kept constant at 15 p.p.m. of phosphate. At times the amount of phosphate entering the system was substantially larger than this because of the intermittent usage of phosphate in the laundry. However, the 15 p.p.m. added to the feed resulted in a final effluent which never failed to show a substantial phosphate content. Although this indicates that the phosphate requirement is satisfied, in view of other features of the process there seems to be no need for seeking the minimum phosphate level.

TABLE II.—*Plutonium removal from laundry wastes by a two-stage trickling filter* [a]

[Summary of selected data for the period from February 1 to July 10]

Duration of Experiment	Observation Period	No. of Obs.	Recirculation Pattern [b]					B.O.D. [c]			Nitrogen						Plutonium [f] Counts/Min./Liter		
			Raw feed	Pri. to sec.	Sec. to pri.	Pri. to pri.	Sec. to sec.	Raw	P.p.m. pri. eff.	Sec. eff.	Ammonia [d]			Nitrate [e]					
											Raw	Pri. eff.	Sec. eff.	Raw	Pri. eff.	Sec. eff.	Raw	Pri. eff.	Sec. eff.
2/1 –2/24	2/15–2/24	6	1	6.6	6.6	-----	-----	335	22	12	26	0	0	0	7	10	731	140	103
2/28–3/20	3/9 –3/20	6	1	-----	-----	12.0	18.0	406	56	18	32	3	0	0	2	5	450	192	134
3/22–4/24	4/7 –4/24	7	1	-----	-----	6.4	22.0	380	26	3	67	10	3	0	16	38	638	145	37
4/24–6/9	5/1 –6/9	15	1	-----	-----	6.4	22.0	213	9	4	17	0	0	0	9	16	325	120	80
6/9 –7/10	6/21–7/10	8	1	-----	-----	6.0	6.0	236	7	2	34	0	0	0	32	38	190	66	46

[a] These data show average B.O.D. removals, nitrogen utilization, and results of plutonium assays for the indicated observation periods and recirculation patterns.

[b] Values listed are ratio of volume recirculated to raw feed to primary filter. Recirculation is from bottom of settling tank. Raw feed maintained at 0.3 million gallons per acre per day.

[c] Raw values are on straight wastes. Primary effluent and secondary effluent values are obtained from samples filtered through Whatman No. 2 fluted filter paper.

[d] Direct nesslerization method.

[e] Phenoldisulfonic method.

[f] Raw values are on straight wastes. Primary effluent and secondary effluent values are obtained from samples filtered through Whatman No. 2 fluted filter paper.

The relationship between the nitrate and plutonium content of the effluent has already been pointed out. A nitrogen balance on the trickling filter system has never been possible. At least two factors may enter into this situation. First, there is the storage of nitrogen by the filter microflora and fauna in the form of organized protoplasm. As a corollary to this storage factor, it may also be expected that due to periodic discharge of biological floc in the cycle of the filter, more nitrogen might be discharged in the effluent at times than entered the filter in the feed. These factors alone are sufficient to preclude the possibility of working out a nitrogen balance on the system. A possible mode for the dissipation of nitrogen lies in the well-known Van Slyke reaction—i.e., under certain circumstances ammonium nitrite may decompose with the formation of gaseous nitrogen and water. Any nitrogen lost in this way could not be accounted for. The possibility that substantial amounts of nitrogen may leave the system in the form of organic nitrogen has been investigated. Organic nitrogen determinations were made on the effluent and the amount of organic nitrogen leaving the system in this way is relatively small in relation to the discrepancy between the nitrogen fed in the form of ammonia and the nitrogen discharged in the form of nitrate.

From examination of the data it has been observed that in all the studies where B.O.D. removal was good and high recirculation ratios used, almost all of the ammonia nitrogen was converted to nitrate in the primary filter. The individual observations have indicated both the storage of nitrogen and releases of nitrogen by the system. The secondary filter does not differ from the primary filter in this respect.

Very little nitrite has been noted in either the primary effluent or the secondary effluent at any time. Apparently with these high recirculation ratios and low loadings the nitrite is almost completely oxidized to nitrate as fast as it is produced.

In this connection it might be well to point out that during the course of the operation of the filter there have been occasional periods when high nitrates were produced in the effluent during a period of relatively low nitrogen feed. It was in fact, the observation of these accidental periods which led to the investigation of increased ammonia feed as a factor in plutonium removal.

In the application of a trickling filter system to the treatment of laundry waste there will be two points of removal of plutonium. First, a certain amount of plutonium will be carried out with the settleable solids that are removed ahead of the filter. It is, of course, possible and may be desirable, to eliminate this step by stirring or mixing the waste before sending it to the trickling filter system. The second point at which the actual plutonium removal will occur is in the suspended solids in the secondary effluent. It is impossible to contemplate this system without either removing the solids from the secondary effluent by very perfect sedimentation or by filtration. In the pilot studies reported long periods have occurred in which the suspended solids have been very low (10 p.p.m.). However, for any sustained operation it is obviously necessary to assume that substantial amounts of plutonium may carry through the system in this fashion. This suspended material may be readily removed by filtrations. During operation of the two-stage trickling filter for the past 6-month period the settlement solids have been very low, less than 0.2%. These solids have been recirculated with the effluents over the filters. This mode of operation did not cause a build-up of settleable solids in the system during the period of study. It is reasonable that sustained operation will cause some increase in the settleable solids in the filter.

CONCLUSIONS

Comparative studies of the chemical precipitation process and of the trickling filter process for removing plutonium from laundry wastes show the following:

1. Either process will effectively remove plutonium from the wastes.

2. The volume of sludge produced by the chemical process will be in the order of 25 to 30 times the volume produced by the trickling filter process. This factor is extremely important since the sludge will contain the plutonium; and handling radioactive sludge is hazardous and complicated. On this basis the trickling filter process appears the more attractive.

3. A trickling filter plant design should provide the following features:

(*a*) A holding tank to allow continuous application of the laundry waste to the filter system at a constant rate.

(*b*) A two-stage trickling filter system with provisions for varied recirculation ratios. Present data indicate that series operation with a recirculation of 6 to 1 or more over each filter will effect the desired plutonium removal. However, it may be necessary to recirculate at a rate as high as 15 to 1 while placing the filter system into operation.

(*c*) Extremely low rates of application of the raw laundry waste with respect to volume and B.O.D. The data show that desired plutonium removal may be effected at an application rate of 0.3 million gallons per acre per day with a B.O.D. loading of about 150 pounds per acre-foot per day, based upon the primary filter.

(*d*) Facilities for adding supplemental nitrogen and phosphorus to the laundry waste before it is applied to the primary filter. The nitrogen may be added in solution as ammonium sulfate and the phosphorus may be added in solution as trisodium phosphate. The amount of nitrogen in the waste should be sufficient and the mode of operation such as to ensure that the final effluent will contain a relatively high concentration of nitrates.

(*e*) The secondary effluent should be filtered to ensure removal of any suspended matter carried over. Exploratory studies indicate that an ordinary rapid sand filter will be effective. The filter backwash should be returned to the laundry waste holding tank.

ACKNOWLEDGMENT

The work upon which this paper is based was performed at Los Alamos, N. Mex., by cooperation of the University of California, United States Public Health Service, and United States Atomic Energy Commission.

LITERATURE CITED

(1) Christenson, C. W. Ettinger, M. B., Robeck, G. C., Hermann, E. R., Kohr, K. C., and Newell, J. F., IND. ENG. CHEM., 43, 1509 (1951).
(2) Huekelekian, H. *Sewage and Ind. Wastes*, 22, 87–93 (1950).
(3) Moore, W. A., Kroner, R. C., and Ruchhoft, C. C., *Anal. Chem.*, 21, 953 (1949).
(4) Newell, J. F., U. S. Atomic Energy Commission, Technical Information Division, Oak Ridge, Tenn., AECD–2712 (1950).
(5) Ruchhoft, C. C., *Sewage Works J.*, 21 877–83 (1949).

Reprinted from SEWAGE AND INDUSTRIAL WASTES, Vol. 25, No. 12, December, 1953
Printed in U. S. A.

ACTIVATED SLUDGE TREATMENT OF RADIOACTIVE LAUNDRY WASTE

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Previous studies (1) on the biological treatment of radioactive laundry wastes contaminated with plutonium have shown that when these wastes are applied to a trickling filter with a high recirculation ratio 80 to 90 per cent of the plutonium is removed. Later studies (2) on laundry waste contaminated with mixed fission products and diluted 1:9 with sanitary sewage indicated similar removals.

Inasmuch as the organisms responsible for the effectiveness of activated sludge treatment are similar to those found in trickling filter slimes and growths, it seemed likely that the activated sludge process would function equally as well. Newell (3) and Ruchhoft (4) have suggested the use of activated sludge treatment in the removal of activity from certain industrial wastes. In the sewage treatment field, activated sludge gives slightly better removal of organic matter than the trickling filter. Therefore, the use of activated sludge treatment seemed to offer considerable promise, except for the fact that there is definite likelihood of excessive frothing in the mixed liquor. This tendency to froth is accentuated in laundry wastes because of the large amounts of detergents or soaps used in the washing process. In previous studies on treatment of laundry wastes by trickling filters there was a considerable accumulation of froth where the filter effluent entered the final settling tank. Apparently the suds were due to detergents. Usually soaps are removed or converted to nonfrothing complexes before reaching the filter effluent. Unusual concentrations of detergents have been reported (5) (6) to have caused frothing difficulties in sewage treatment plants. Although occasional difficulties of this type can be controlled by anti-foaming agents, the continuous application of these agents to sewage containing a high percentage of laundry waste would not be practical.

The Problem

At new AEC installations, as well as at some established projects, the problem of what to do with comparatively small volumes of radioactive laundry waste often confronts the designing engineers. These wastes usually contain a rather low concentration of radioactive materials, so that treatment providing 80 to 90 per cent removal is adequate. As noted previously, treatment on trickling filters ordinarily will accomplish this removal. The capital investment in an activated sludge plant is considerably less than that of a trickling filter plant and it might be expected that higher removals could be obtained. Although operating expenses are generally higher for the activated sludge plant than for a trickling filter plant, and more exacting control is required for

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best operation, it is conceivable that lower construction costs would make the activated sludge process more attractive in some instances. For this reason it was decided to investigate the various problems involved in the use of activated sludge treatment of the wastes.

From a cost standpoint the possibility of treating both laundry waste and sanitary sewage in the same plant appears inviting. The combined treatment plant would need be only slightly larger than a plant for treating sanitary sewage alone, and by diluting the laundry waste with sanitary sewage the concentration of detergents or soaps would be greatly decreased so that sudsing might not be a problem. Unfortunately, some problems connected with the disposal of radioactive sludge would be increased, as a greater amount of contaminated sludge would require disposal under these conditions.

Objectives of the Study

Because of these several questions regarding the use of activated sludge treatment on laundry wastes, it was evident that considerable investigational work was needed before a sound opinion could be given on the best process for a particular installation. Therefore, the present study was initiated to provide information on the following points:

1. To determine whether activated sludge treatment would give satisfactory results on a mixture of laundry waste and sanitary sewage when a high suspended solids content of mixed liquor is used.
2. To provide information on the process when a low suspended solids content is carried in the mixed liquor.
3. To determine to what extent the activity accumulates in the zoogleal sludge.
4. To determine whether digester supernatant can be returned to the aeration basin without upsetting the process.

The dilution ratio of 15 per cent laundry waste and 85 per cent sewage was chosen because this particular ratio was estimated for an AEC installation where design data were needed. Prior to the start of the study the Los Alamos contaminated clothing laundry had started the practice of using only soap for a softener and cleansing aid, rather than a mixture of soap and synthetic detergent as had been the previous practice. This was done because soaps are more susceptible to biological oxidation than synthetic detergents and therefore would be more completely removed in any biological waste treatment process. Furthermore, soaps give less trouble from frothing and the clothing is decontaminated as well with soap as with the combination of soap and detergent. In this connection it should be mentioned that the Los Alamos water supply is naturally soft and there are only small quantities of calicum and magnesium precipitates.

Laboratory Studies

The sewage used for these experiments was collected from an 8-in. sewer carrying only domestic sewage and was strained through four layers of cheese cloth to simulate a 2-hr. settling period. The sewage was fresh at the time of collection.

The laundry waste used consisted of a composite sample from the discharge of the industrial laundry collected over a 6-hr. operating period.

Apparatus

The activated sludge studies were all carried out in 20-l. wide-mouth pyrex bottles with the liquid level maintained at the 16-l. mark. Air was supplied by means of a small porous diffuser ball submerged to the bottom of the bottle. The flow of air was regulated so as to just keep all of the sludge in suspension, but no attempt was made to measure the aeration rate.

A fill and draw arrangement with one draw-down a day was used throughout.

Method of Operation

The method of operation was as follows: The air diffuser was shut off at 8:30 A.M., the sludge settled for 1 hr., and the supernatant drawn down to the sludge level, which was usually between the 5- and 6-l. level. A raw feed mixture of 15 per cent radioactive laundry waste and 85 per cent settled domestic sewage was then added in sufficient quantity to bring the liquid level to 16 l. and aeration was resumed for the remainder of the 24-hr. period (approximately 22.5 hr.). On the first study in which high suspended solids levels were maintained, 300 ml. of settled sludge were withdrawn at weekly intervals for plutonium analysis. This also served the purpose of holding down the suspended solids in the mixed liquor to a practical level. On the second study a small amount of sludge was withdrawn daily for the purpose of holding the suspended solids concentration in the mixed liquor at approximately 1,500 p.p.m. Daily pH measurements were made of the effluents; dichromate oxygen consumed determinations (7) were made twice weekly. Other tests on the effluents (such as plutonium counts, ammonia nitrogen, nitrate nitrogen, and phosphate) were made at weekly intervals, or in some instances less frequently. The determinations on the mixed liquor, including suspended solids, ash content, and settleable solids, were made at weekly intervals. The concentrations of plutonium and oxygen consumed in the raw mixture were calculated from the analytical results on samples of undiluted laundry waste and settled sewage. In general, the laundry analyses were made at weekly intervals or more frequently, whereas the sewage analyses were made at about two-week intervals.

The raw laundry waste showed an average oxygen consumed value of 700 p.p.m. and a plutonium concentration of 1,726 counts per minute per liter during the first run. As might be expected, the fluctuation in strength of this waste was very great with respect to both O.C. and activity.

Summaries of Results

A summary of the data collected on activated sludge treatment of a mixture of 15 per cent laundry waste and 85 per cent settled sewage is given in Table I. On the run from November 8, 1951, to July 30, 1952, the suspended solids concentration in the mixed liquor was maintained at a high level so as to simulate the typical activated sludge plant in which compressed air is applied by means of porous diffusers. As was to be expected from the long aeration period, the effluent O.C. and B.O.D. values were very low, indicating excellent stabilization of organic matter. Furthermore, the residual plutonium concentrations were very low, showing an average value of 30 counts per minute per liter, or 2.7×10^{-5} μc. per l. Since the plutonium concentration in the raw mixture was 259 counts per minute per liter, or 2.33×10^{-4} μc. per l., this represents a reduction of 88.4 per cent. Suspended solids in the mixed liquor averaged 3,025 p.p.m. and contained 25.5 per cent ash. These solids settled to a volume of 345 ml. per liter after 30 min., indicating excellent settleability. There was no trouble experienced from frothing during any of these experiments. One of the most interesting features of the study was the build-up of plutonium in the sludge. The average value for plutonium was 7,000 counts per minute per gram of dry sludge or 6.3×10^{-3} μc. per gram. There was considerable variation, which could not be accounted for, in these results on sludge. However, since the activity in the sludge that was withdrawn during the entire run was essentially the same as the amount added with the laundry waste,

TABLE I.—Summary of Experimental Data on Activated Sludge Treatment of Radioactive Laundry Waste [1]

Item	High Susp. Sol. in Mixed Liquor[2]				Low Susp. Sol. in Mixed Liquor[3]			
	Av.	Max.	Min.	No. of Results	Av.	Max.	Min.	No. of Results
Raw laundry waste:								
Oxygen cons. (p.p.m.)	700	1,980	140	83	588	860	420	20
Pu (counts/min./l.)	1,726	35,900	170	108	2,642	35,900	410	47
pH	6.7[4]	7.5	4.9	85	7.1[4]	7.4	6.3	22
Settled sewage:								
Oxygen cons. (p.p.m.)	145	186	103	12	145	186	103	12
Raw mixture:								
Oxygen cons. (p.p.m.)	228[5]	—	—	—	211[5]	—	—	—
Pu (counts/min./l.)	259[5]	—	—	—	396[5]	—	—	—
Mixed liquor:								
Susp. solids (p.p.m.)	3,025	4,398	1,440	44	1,612	2,260	1,120	25
Ash (%)	25.5	39.7	12.6	42	20.0	22.1	17.0	24
Settl. sol.[6] (ml./l.)	345	770	155	43	134	215	100	25
Sl. density index[7]	0.96	1.44	0.42	41	1.25	1.63	0.70	25
Effluent:								
Oxygen cons.[8] (p.p.m.)	24	45	4	69	23	55	4	50
B.O.D.[9] (p.p.m.)	6	9	3	6	—	—	—	—
Pu[8] (counts/min./l.)	30	118	0.4	33	19	73	0	22
NH_3—N (p.p.m.)	0.58	5.7	0	10	0.28	2.2	0	9
NO_3—N (p.p.m.)	30	38	23	10	29	41	13	10
PO_4 (p.p.m.)	18	22	10	10	18	25	9	10
pH	7.7[4]	8.6	6.0	243	7.5[4]	9.4	5.8	151
Sludge:								
Pu (counts/min./l.)	65,800	—	—	31	—	—	—	—
Pu (counts/min./g. dry sol.)	6,967	—	—	31	—	—	—	—

[1] Mixture of 15 per cent laundry waste and 85 per cent settled domestic sewage.
[2] November 8, 1951 to July 30, 1952.
[3] February 12, 1952 to July 30, 1952.
[4] Median value.
[5] Calculated value.
[6] Settled for 30 min.
[7] $\frac{\text{P.p.m. suspended solids}}{\text{Ml. settled sludge} \times 10}$.
[8] Filtered.
[9] Settled.

it is believed that the average values are substantially correct.

During the period from February 12, 1952, to July 30, 1952, the suspended solids concentration of the mixed liquor was maintained at approximately 1,500 p.p.m. Furthermore, all excess sludge was digested in a 10-l. bottle, the supernatant being returned to the aerator bottle. These data show that the effluent oxygen consumed values are quite similar (23 p.p.m.) to those of the other study, so it is evident that the supernatant return and low suspended solids content did not adversely affect the results. Plutonium removals are slightly better on this series, the average effluent count amounting to 19 counts per minute per liter (1.7×10^{-5} μc. per l.) giving a removal of 95.2 per cent. The average suspended solids value was 1,612 p.p.m. and the settleable solids were 134 ml. per l. in 30 min. Phosphate values were quite high on both studies, no doubt due to the large amount of detergents used by the people in the community from which the sewage was collected. Nitrate values were quite high, as might be expected from the

long aeration periods. In this study no attempt was made to find the amount of plutonium concentrated in the sludge.

The effects of shorter aeration periods and larger percentages of laundry waste are being studied. The results of these studies are to be reported at a later date.

Conclusions

From the information gained from this study the following conclusions can be drawn:

1. The activated sludge process is satisfactory for the treatment of a mixture of 15 per cent radioactive waste from the Los Alamos industrial laundry and 85 per cent settled sewage. Both plutonium and organic matter removals were excellent under the conditions of the experiments, which included long aeration periods, as well as filtration of effluents, before analytical determinations for plutonium and oxygen consumed were made. Frothing was not a problem with this mixture, as no synthetic detergents were used by the laundry during the period of the study.

2. With the long aeration periods used, the results were equally good at both high and low suspended solids concentrations in the mixed liquors.

3. Return of the digester supernatant to the aeration tank did not have a detrimental effect on the process.

4. Concentration of plutonium in the zoogleal sludge was found to be rather high, even though the concentration in the raw feed was definitely at a low level. This demonstrates that zoogleal sludge is an effective concentrator of plutonium. Because of this fact, all excess sludge from a full-scale treatment plant would require special handling and disposal to prevent the scattering of long-lived radioactive materials to the general environment.

References

1. Newell, J. F., Christenson, C. W., Mathews, E. R., Ruchhoft, C. C., Krieger, H. L., and Moeller, D. W., "Laboratory Studies on Removal of Plutonium from Laundry Wastes." *Ind. Eng. Chem.*, **43**, 1516 (1951).
2. Unpublished data from files of Industrial Waste Section, Health and Safety Branch, AEC, Los Alamos, N. M.
3. Newell, J. F., "Exploratory Studies on the Removal of Plutonium from Liquid Wastes by Activated Sludge." AECD–2712, Tech. Inf. Div., Oak Ridge, Tenn. (1950).
4. Ruchhoft, C. C., "The Possibilities of Disposal of Radioactive Wastes by Biological Treatment Methods." *Sewage Works Jour.*, **21**, 5, 877 (Sept., 1949).
5 Anon., "What Caused the Suds in the Sewage Treatment Plant?" *Amer. City*, **42**, 12, 99 (1947).
6. Editorial, "Synthetic Detergents and Sewage Treatment." *Sewage Works Jour.* **20**, 3, 578 (May, 1948).
7. Moore, W. A., Kroner, R. C., and Ruchhoft, C. C., "Dichromate Reflux Method for Determination of Oxygen Consumed." *Anal. Chem.*, **21**, 953 (1949).

PILOT PLANT FOR DECONTAMINATION OF LABORATORY LIQUID WASTES

by K.A.Bolshakov, A.T.Avdonin, V.T.Borchev, F.V.Rauzen and others

Recent developments in radioisotope production and usage have given rise to a new problem - decontamination of liquid wastes. This problem has appeared to be extremely difficult in laboratories of research institutes, since there chemical and radio-chemical composition of liquid wastes as well as their daily consumption greatly vary.

The decision to build a pilot plant designed to decontaminate liquid wastes for a group of research institutes including chemical, physical and biophysical laboratories was the first practical attempt to solve this problem. But some additional difficulties arose owing to the fact that wastes of biophysical laboratories contain large quantities of organic substances.

The present paper describes the flow chart of this pilot plant and its operation.

Composition and nature of wastes

The major flow of liquid wastes to the plant is usually observed from 9 a.m. till 8 p.m. i.e., during the working day at the institutes.

The radioactive wastes result from washing, laboratory rooms and equipment, animals under experiment and their cages, laundry etc.

According to the character of their contamination all these wastes may be divided into the following three groups:

1. Wastes of chemical and physical laboratories;
2. Wastes of biophysical laboratories;
3. Wastes of special laundries.

Data on liquid waste approximate composition are given in Table I below.

Table I

Nos.	Contaminant	ppm		
		Wastes of chemical laboratories	Wastes of biophysical laboratories	Wastes of laundries
1.		2.	3.	4.
1.	Sodium, Na	92	62	359
2.	Calcium, Ca	40	80	2
3.	Magnesium, Mg	18	18	1.2
4.	Ferric oxide	2.8	-	-
5.	Ammonia	0.18	1.1	0.2
6.	Potassium, K	-	33	11.2
7.	Manganese, Mn	-	-	8.2
8.	Bicarbonate	85	67	79.2
9.	Nitrates	99	31	-

1.	2.	3.	4.
10. Chlorides	46	96	241.5
11. Chromates	0.6	-	-
12. Sulphates	14	48	91.2
13. Silica	106.5	106.5	106.5
14. Sulpho-naphtenic	38.2	13.9	174
15. Oil and other organic substances	40	41.4	160
16. Total quantity of different salts	622	1040	1756
17. pH	7.8	8	5.5
18. Concentration of α-emitters, curie/litre	$1x10^{-7}$	$1x10^{-9}$	$1x10^{-7}$
19. Concentration of β- and γ-emitters, curie/litre	$1x10^{-7}$	$1x10^{-7}$	$1x10^{-7}$
20. Biochemical oxygen demand, (B.O.D.) ppm	5 - 10	300 - 350	250-300

*/ Sulpho-naphtenic acids are components of "petroleum oil contact" agent being used to wash the surfaces contaminated with radioactive elements. The "petroleum oil contact" agents are obtained by treating high-temperature oil refinery products with sulphuric acid.

The table shows that these three groups of liquid wastes are quite different in their composition, however, wastes of the biophysical laboratories and laundries have one common feature–their high B.O.D. caused by high content of

organic substances.

Flow Chart

The possibility of treating radioactive wastes is known to have been studied recently by physical, chemical and biological methods for industrial and sewage waters.

Among these evaporation methods (1-3) have been practised on a large scale, though in some case ion-exchange methods (4,5) appear to be more economical. Besides, chemical treatment (the use of carrier-precipitant to deposit radioactive elements) and biological treatment (6-13) are also used to decontaminate radioactive wastes.

The efficiency of each method depends upon the chemical and radiochemical composition of effluents.

It is the ion-exchange method that is accepted at the pilot plant as the basic method for decontamination of laboratory wastes.

A technical and economical comparison of evaporation and ion-exchange methods, their decontamination factor being satisfactorily high, has shown that evaporation methods are approximately 2 times as expensive as the ion-exchange methods.

Preliminary laboratory experiments have shown that considerable concentrations of organic and colloidal substances in effluents considerably reduce the effect of the decontamination by ion-exchange method. It is for these reasons that wastes of biophysical laboratories and special laundries are separated in a special group.

These effluents are usually given preliminary biological treatment and only after that are directed together with wastes of physical and chemical laboratories for coagulation.

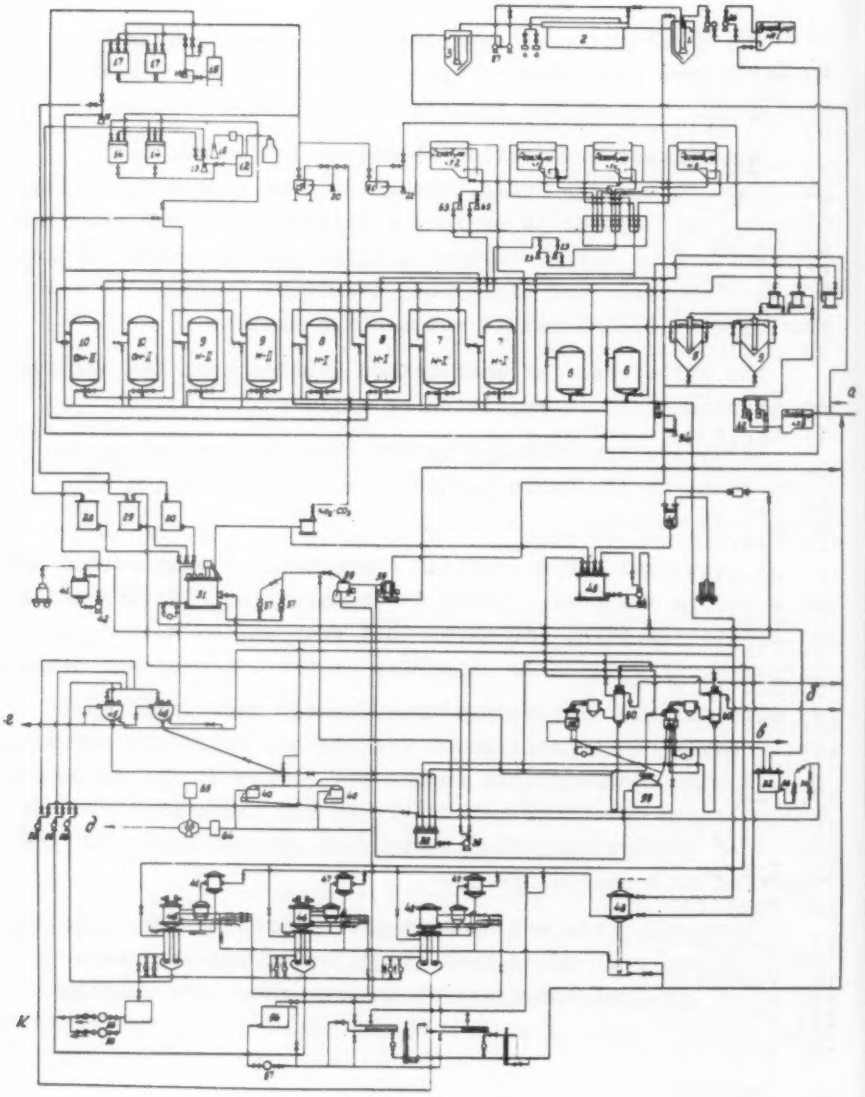

Fig.1. Flow chart.

a) from water pipe
b) Technological layout of special drain water purifying station
c) d) delivery collector
e) Solution of H_2SO_3
f) to hot water collector
g) to the grave for ground disposal
h) to special canalization
j) to boiler collector
k) condensate to boiler room.

1. Primary settler (vertical)
2. Aerotank
3. Secondary settler (vertical)
4. Air blowers
5. Clarifiers
6. Mechanical filter
7. First-stage filters of cation exchangers
8. First-stage filters of anion exchangers
9. Second-stage filters of cation exchangers
10. Second-stage filters of anion echangers
11-12. Nitric acid tank
13. Pump for piping nitric acid solution
14. Nitric acid solution preparation tank
15. Hydraulic stirrer for sodium hydroxide
16. Pump for sodium hydroxide solution
17. Sodium hydroxide solution preparation tank
18. Vacuum-pump
19. Hydraulic stirrer for sodium carbonate
20. Pump for sodium carbonate solution
21. Coagulant preparation stirrer
22. Pump for coagulant
23. Pump for wastes
24-25. Pump for regenerates

26-27. Pumps for activated sludge
28. Alkali regenerate solution collector
29. Acid regenerate solution collector
30. Other solutions collector
31. Neutralizing reactor
32. Tank
33-34. Collectors
35-36-37. Pump for solution
38. Pump for condensate
39-40. Centrifuge
41. Vacuum-tank
42. Pump for solution
43. Tank for solution
44. Pump for solution
45. Reactor-crystallizer
46. Evaporator
47. Catcher
48. Barometric condenser
49. Evaporator
50. Batcher for acid reagents
51-52. Batcher for alkali reagents
53. Cooling water pump
54. Pump for sludge
55. Tank for sodium carbonate solution
56. Tank for filtrate
57. Pump for filtrate
58. Pump for evaporated solution
59. Container charging cabinet
60. Aerosol removal column
61. Pump for condensate
62. Pump for special wastes
63. Washing pump
64. Pulp batcher
65. Cement batcher

66. Concrete mixer.

a. Delivery collector
b. to special sewage system
c. to steam collector
d. to hot water collector
e. to a grave for ground disposal
f. condensate to boiler room.

Fig.1 presents a flow chart of a decontaminating plant.

The wastes of the biological group are subjected to primary settling, treatment with activated sludge and then to secondary settling. This being done, the waters are mixed with other wastes and are subjected to preliminary decontamination (coagulation, clarification and filtration). After that the wastes are directed into intermediate storage tanks where their activity is measured. Then they are subjected to ion-exchange treatment and drained off into natural water basins.

In the primary settling tank radioactive elements are deposited together with suspended solids and an excess of activated sludge, in the clarifier - together with hydrated pulp, and in the ion-exchange filters - together with regenerates.

These products concentrating radioactive elements removed from liquid wastes during the processes mentioned above are then specially processed to solidify them for subsequent disposal into the ground.

In conformity with the flow chart the plant has the following sections:

a) Section of biological decontamination
b) Section of chemical and ion-exchange decontamination
c) Section for processing slime and regenerates
d) Section for reagent preparation.

1. Section of Biological Decontamination

Biological decontamination process has the following stages (see Fig.1): liquid wastes flow by gravity collector to storage tank 1 which serves as a regulating tank. From this tank wastes are pumped (by pump 26) to primary settler (1).

Pumping in this case ensures desirable uniform fleed of effluents. From the primary settler wastes flow by gravity to aerotank (2) where they are treated with activated sludge: then they flow also by gravity into secondary settler (3). To maintain effective working capacity of the activated sludge the air is continuously supplied to the aerotank.

It has been found out that the active biological growth is normal. Content of radioelements in effluents is reduced by not more than 50 per cent, but owing to oxidative assimilation which destructs organic substances in wastes their B.O.D.is reduced from 300-400 p.p.m. to 15-20 p.p.m. and that is the main objective of biological treatment of wastes as a preliminary operation.

From secondary settler (3) effluents flow into receiver where they are mixed with other wastes and then are directed for ion-exchange treatment.

Activated sludge from the secondary settler is pumped (by pump 27)to aerotank(2), while its excess is pumped to primary settler. The feed of the excess of activated sludge into the primary settler has two purposes:

1) improving the operation of primary settler (1)
2) removing of activated sludge from one apparatus only.

From primary settler (1) sludge is pumped (by pump 53)

to a section for processing slime and regenerates. The sludge contains 10^{-6} curie of radioelement per one kilogramme of dry weight.

2. Section of Chemical and Ion-Exchange Decontamination

The wastes in this section are processed in the following way:

From receiver the wastes are pumped (62) to clarifiers (5) and settle there after the addition of a coagulant which is pumped in through a tube .

The coagulation process is aimed at the removal of suspended and colloidal particles from the wastes i.e., their clarification. This process can be carried out with usual coagulants. But the coagulation process is also aimed at the partial removal of some radioelements (zirconium, niobium, polonium, uranium, cerium and rare-earths and others) from the wastes.

Coagulants differ by their efficiency. Figure 2 illustrates the dependence of the degree of clarification on the dose and composition of coagulants agents.

These investigations made it possible to choose ferric sulphate (100 p.p.m.) as a coagulant for the pilot plant. The coagulation process is carried out in alcaline medium (pH = 8-9). Coagulant dosage is made with washer-type batcher (51).

The volume of the slime settled in clarifiers equals usually to 0.7 per cent of the volume of initial wastes. This slime is then delivered to the section for processing slime and regenerates where it is treated to decrease its water content.

The wastes clarified flow by gravity to mechanical

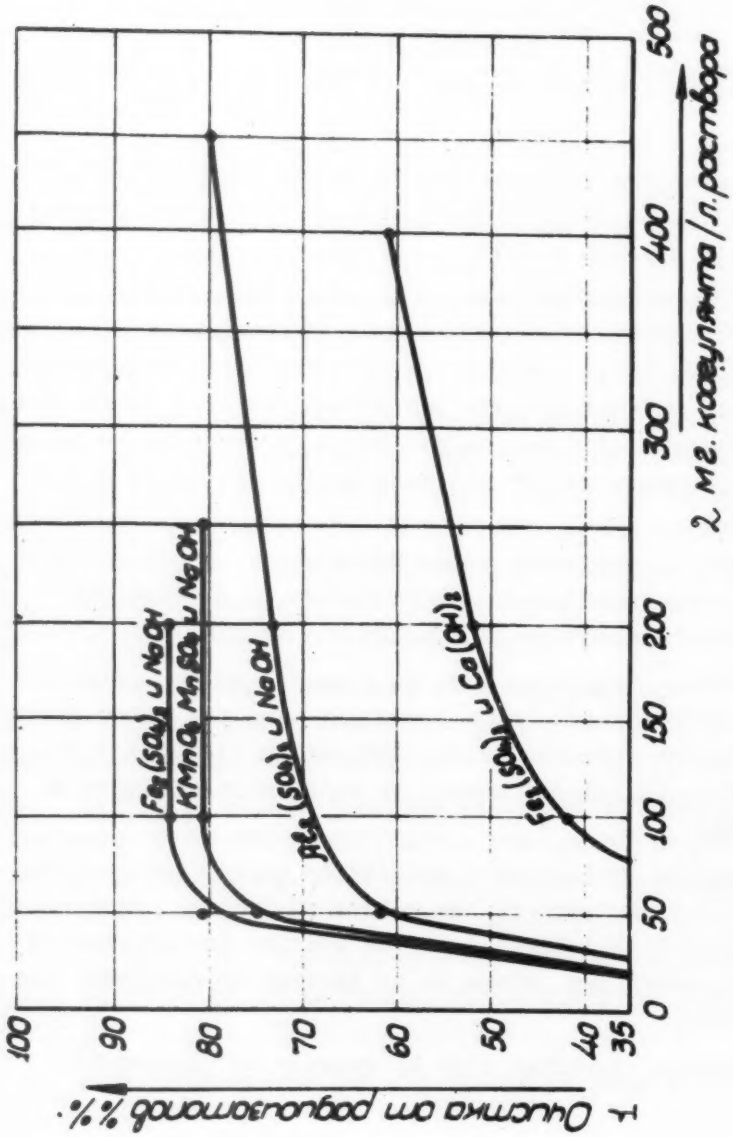

Fig.2. Removal of β-emitters by coagulation

1. Removal of radioisotopes (%)
2. Milligrams of coagulant per litre of solution.

filters (6) charged with sand and anthracite and designed to catch suspended particles brought here from the clarifier.

From these filters some wastes are pumped (pump 54) to intermediate storage tanks 3, 4 and 5.

The intermediate tanks are designed to carry out the following two functions:

1) they serve as buffer basins which allow to vary the rates of operation of clarifiers and ion-exchange filters;

2) they make it possible to control the activity content of the wastes after their coagulation.

During the process of clarification some radioelements are removed from the wastes together with slime.

The rate of removal is different: for different radioisotopes zirconium and rare-earths - up to 90-95 per cent, ruthenium by 30-40%, strontium- by 20-30 per cent, while the concentration of caesium remains practically unchanged. Then dosimetric control is effected and the wastes from the intermediate storage tanks are released into a discharge collector (provided that their radioactivity level does not exceed sanitary standards) or pumped (pump 62) for additional decontamination by ion-exchange filters.

Effluents which are pumped to the ion-exchange filters contain radioactive isotopes of caesium and strontium (in most cases strontium-90 + yttrium-90 for which permissible sanitary standards are exclusevely low and should be strictly observed).

The extent of decontaminating factor of elements depends upon the content of alkali and alkali-earth elements content in effluents (sodium, potassium, calcium and magnesium).

Two-stage decontamination with the use of the ion-exchange filters is used. At each stage a solution is being successively filtered through cation and anion exchange resins.

The first stage filters remove from water the bulk of inactive salts, while the second stage effect a greater

2. Milligrams of coagulant per litre of solution.

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decontamination of solution (which at this stage is almost free of salts).

Upon two-stage treating with ion exchange resins the decontamination factor of 10000-100000 is attained.

The first and second stage filters operate according to H-OH chart which is designed to remove entirely all the salts from the water. Cation exchange resin КУ-2 and anion exchange resin АН-2Ф are used.

At the first stage the solution passes through two columns of cation exchangers therefore only acid solution has access to the first-stage anion exchanger, the regeneration of the cation exchange resins being carried out after calcium ions have been traced in the solution. The succesive operation of the columns is shown in Fig.3.

The first column of the cation exchanger is regenerated after the appearance of calcium ions in the solution. After the recovery of the column the order is changed: the solution passes through column 2 and then - to column 1 and so on. Column 3 always receives solutions with pH = 2-3, which ensures high capacity of the anion exchanger.

It is very seldom that the second-stage columns are recovered since they usually receive water practically free of salts.

To ensure continuous operation of the system it is equipped with spare cation exchange and anion exchange columns at the first stage.

The rate of solution filtration has been chosen so as to ensure that the value of the specific load $\left(\frac{\text{solution consumption, m}^3/\text{hour}}{\text{ion-exchanger bed, m}^3}\right)$ does not exceed 6.

The regeneration of cation exchange resins is usually

Fig.3. Successive operation of ion-exchange columns
1- First stage; 2 - Second stage; 3 - Contaminated water; 4 - Column; 5 - Cation exchanger; 6 - Anion exchanger; 7 - Decontaminated water.

carried out with 5% - solution of nitric acid, while the regeneration of anion exchange resins - with 2.5% - solution of sodium hydroxide.

The volumes of acid and alkali used for regenerator are 3 times as great as the volume of ion exchanger bed.

Regenerates are delivered into filters upward which makes it possible to reduce their consumption. The solution is supplied in two portions: the first portion, after the recovery process is over, is pumped to a receiver of the section for processing slime and regenarates, and the second portion - to empty tanks of the Section for reagent preparation where they are reused.

Water used for the first washing of the filters is also pumped into tanks of the Section for reagent preparation and after the addition at a proper reagent is used for the second time.

3. Section for Processing Slime and Regenerates

This section is designed to minimize the volume of slime and regenerates.

Regenerates processing is carried out according the following flow chart:

1) Neutralizing solutions and precipitation of calcium and magnesium salts;

2) Filtration of residue precipitated during the neutralization process;

3) Evaporation of a neutralized solution;

4) Crystallization from an evaporated solution;

5) Separation of sodium nitrate crystals;

6) Packing solid residues into a container for ground disposal.

Regenerates from the chemical section are piped into tanks (28,29) and hence - into reactor (31) for the neutralization and the precipitation of carbonates. Some quantity of sodium carbonate is added to the reactor from tank (55).

In the reactor the solution is heated with steam through a steam jacket. After the neutralization process is over, the pulp is pumped (37) from the reactor into a settling centrifuge (39) where the residue precipitated in the reactor is separated.

The residue contains ferric, manganese and magnesium hidroxides as well as calcium carbonate, oxalate and phosphate. Some of the radioactive substances is collected in this residue. The volume of the residue amounts to 70 litres per 100 m^3 of the solution delivered for ion-exchange, the residue activity being equal to 0.5 $\frac{mc}{kg}$.

Filtrate is poured off into a tank (56) and the residue is discharged into a container and transported to disposal places, while the filtrate is then pumped (pump 57) from the tank to evaporators (46). The evaporation of the solution is a continuous-periodic process.

The volume of solution delivered to the evaporator is equal to the volume of evaporated water; the evaporation of the solution is carried on until the solution is saturated with sodium nitrate; the solution level in the evaporator being kept constant. On attaining the saturation of the solution the evaporator is emptied with a pump and then is filled again with a fresh solution of initial concentration. The evaporated solution is then pumped (45) for crystallization.

To prevent crystallization of the solution in the pipes and inside the pumps the latter is preheated with steam, and after the solution has been discharged from the apparatus it is washed with initial solution.

Then the solution in the crystallizers is cooled (through water jacket) to 20-25°C by fresh wastes.

The cooling process is usually accompanied with the stirring of the solution with a frame stirrer. The crystallization process being over, the pulp is drained off into a filter-type centrifuge (40).

The filtrate is drained off into a collector (34), while the residue is discharged from the centrifuge into a container and transported for ground disposal. The volume of this residue is 0.08 per cent of the initial.wastes.

The activity of the sodium nitrate residue after its washing is not considerable and therefore it is usually dissolved in clean water and drained off into drain collector. The filtrate from the collector is pumped (pump 35)to evaporators (49) for final evaporating and here it is evaporated up to the point when it still can be easily discharged into the containers. This evaporated solution is drained off into the containers through a bottom pipe union.

Steam from evaporators (49) passes to the special columns (60), where active aerosols are decontaminated. The upper part of the column is provided with heat exchanger designed to concentrate a certain amount of steam (from 5 to 10%) for the formation of the reflux. The condensate from the column is drained off into the collector (34).

The decontaminated steam then passes into the mixing condenser (48) which is watered with wastes which have been previously subjected to preliminary mechanical decontamination From the condenser the mixed wastes are delivered to

intermediate storage tanks. Heating steam condensate from the apparata (31, 46,49) is collected in a tank (32) and henceforth it pumped (pump 61) to a boiler room.

The water content of the slime is decreased in centrifuges; its volume becoming 50 times less than that of the slime discharged from the clarifier. After this slime and sludge are solidified by mixing them with cement. The practice has shown that the mass of highest density is formed when the so called "putso-lanian" cement is used for this purpose, the density of the mass depending upon the ratio of the wet residue volume and the cement weight.

When this ratio = 1 the density of the mass amounts to 130 kg/cm^2; a 1.5 - 2 times increase in the ratio decreases the density of the mass by a factor of 2 or 3. The mass before it becomes solid is discharged into graves whose bottoms and walls are given special treatment to make them waterproof. Thus the radioactive wastes are disposed into the ground.

4. Section for Reagent Preparation

The section provides for the preparation of the following reagents:

a) 5% - solution of nitric acid;

b) 2.5% - solution of sodium hydroxide;

c) 5% - solution of coagulant; and

d) lime.

Concentrated solutions of sodium hydroxide, coagulant and lime are prepared in hydraulic mixers (12, 19, 21) with the help of pumps (12, 20,22). Since the consumption of sodium hydroxide, coagulant and lime is small, these

substances are delivered into the hydraulic mixer manually.

From the mixer the solution of coagulant and lime is piped with the same pumps to the washer-type batcher (50) and the solution of sodium hydroxide - to tanks (14) where it is diluted with water up to the concentration desirable.

The preparation of a solution of an acid is carried out as follows: acid is supplied to the section in containers; then it is piped into the intermediate tank (15) by a vacuum pump; henceforth it is pumped (pump 16) into tanks (17)where it is mixed with water up to the desirable concentration.

Operation Control

To control the operation of mechanisms and apparata a remote control system with the central control post is provided. This post is located on the second floor of the building. Besides, a direct control of different apparata in the operation zone is provided. This provides the possibility for the initial set up and the testing of these apparata. Locking and regulating devices of these apparata are provided with electric drives.

The recovery of ion-exchange filters (after they are switched off) is carried out automatically with master apparatus which makes it possible to raise the quality of this process.

The following variables are regulated:

1. temperature,
2. level,
3. solution consumption,
4. turbidity,
5. pressure,

6. pH,

7. decontamination factor.

The control is effected from the central control post which is equipped with central control panel and a control desk. The central control panel is provided with all the secondary instruments which control the main variables of the process.

Local panels are equipped with instruments which repeat the readings received from the central control panel; this facilitates greatly the initial setting up of the process. To control the personnel-safety the continuous control system is provided. To control the degree of air contamination, control filters are installed.

The personnel is regularly subjected to special dosimetric control.

Conclusion

The present paper describes the flow chart of a pilot plant for the decontamination of laboratory wastes.

As a result of this treatment radioactive elements are removed from wastes up to the concentration when the drainage of these waters into natural water basins is quite safe.

Radioelements are concentrated in slimes, sludges and regenerates which are subjected to further processing for their solidification.

The volume of the solids to be disposed to the ground is less than 0.1 per cent of that of the initial wastes.

REFERENCES

1. Frank N.B. Browder, "Liquid Waste Disposal at Oak Ridge National Laboratory". Ind. and Eng.Chem. 43, 1502-1505,(1951).

2. G.E.Mc Cullough. "Concentration of Radioactive Liquid Waste by Evaporation". Ind. and Eng.Chem.43, 1505-1509, (1951).

3. Charles E.Hirseh. "How Hanford Evaporates Fission Wastes". Chem.Eng.60, No.11, 184-185,(1953).

4. John A.Ayres. "Treatment of Radioactive Waste by Ion Exchange". Ind. and Eng.Chem.43, 1526-31,(1951).

5. H.Gladys Swape and Elaine Andersom. "Cation Exchange Removal of Radioactivity from Wastes". Ind.and Eng. Chem. 47, 78, (1955).

6. C.W.Christenson, M.B.Ettinger, G.G.Robeck, E.K.Hermann a.u. "Removal of Plutonium from Laboratory Wastes". Ind. and Eng.Chem. 43, 1509-1516,(1951).

7. Conrad P.Straub. "Limitations of Waster Treatment Methods for Removing Radioactive Contaminants".Public Health Reports, 70, 897,(1955).

8. R.A.Landerdele."Treatment of Radioactive Wastes by Phosphate Precipitation". Ind.and Eng.Chem. 43, 1538-40, (1951).

9. S.Goodgol, Eanrnest F. Gloyna and Dayton E.Carritt. "Reduction of Radioactivity in Water".J.A.Water Works Assoc. 46, 66, (1954).

10. C.C.Ruchhoft H.T. Kringer and D.W.Moeller. "Laboratory Studies on Removal of Plutonium from Landry Wastes".Ind.and Eng.Chem.43,1516-1519,(1951).

11. "AEC builds first full-scale plant for radioactive Wastes". Eng. New-Record, 151, 2,37(1953).

12. C.C.Ruchhoft and L.R.Setter."Application of biological Methods in the treatment of radioactive Wastes". Sewage and Industrial Wastes 25, 48-60,(1953).

13. G.E.Eden, G.H.J.Elkens and G.A.Truesdule. "Removal of radioactive substances from Water by biological treatment process".Atomics 5, 133-142, 158,(1954).

Representative HOLIFIELD. I want to thank the witnesses today for their testimony and the audience for their very close attention.

Tomorrow, we will meet in room F–39 at 10 a.m. That is the appropriations room, one floor down, the northwest end of the Capitol Building on the Senate side.

Thank you very much.

(Whereupon, at 4:45 p.m., Thursday, January 29, 1959, the hearing was recessed, to reconvene at 10 a.m., on the following day.)

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